A PROBABILISTIC MODEL FOR POWER QUALITY REGULATION BASED ON YARDSTICK COMPETITION

José M. López Sánchez
Unión Fenosa Distribución
Madrid, Spain
jlopezs@uef.es

Tomás Gómez San Román
Instituto de Investigación Tecnológica (IIT)
Universidad Pontificia Comillas
Madrid, Spain
tomas@iit.upco.es

Abstract – The regulation of the electricity distribution utilities has evolved to a scenario based on competition and cost-effectiveness. This cost reduction may affect the quality performance. A quality regulatory proposal based on yardstick competition is presented. The competition is against objective values of the selected zonal quality indices that are computed using a probabilistic model that takes into account the historical behavior of the distribution network. A monitoring scheme has been developed to obtain the basic reliability indices from the rough data. A methodology to segment the supplied area and an incentive/penalty scheme to encourage utilities to improve their quality indices are proposed. The implementation plan of the regulatory proposal is briefly outlined. Finally an implementation study case of the scheme is shown.

Keywords: Power quality, Distribution regulation, Yardstick competition, Reliability, Electricity markets, Probabilistic models, Economic Penalties

1 INTRODUCTION

The regulation of electricity distribution has evolved to an increasing competitive scenario based on efficiency improvements. This kind of regulation provides incentives to cost reductions made by distribution utilities. Since reliability and consequently power interruptions are strongly related to investments, and operation and maintenance practices, there exists the possibility that this cost reduction might affect the quality performance of the distribution systems. Besides, the whole society is increasing the awareness for the aspects related to the quality of service.

This paper presents a regulatory proposal to guarantee the quality of service provided by distribution utilities ready to be implemented under these circumstances. This proposal is based on yardstick competition, wherein the competition among utilities is made by comparison of power quality levels provided by each utility against pre-specified objective values. The objective values are assessed using a probabilistic model that takes into account the historical reliability levels provided by the regulated utilities in the past. Utilities that perform better than objective values receive additional revenues while those utilities that perform worse are economically penalized.

Distribution system reliability evaluation has been generally concerned only with the average values of reliability indices. Given the random nature of faults and interruption causes and hence the random nature of reliability indices it is critical in order to set the objective quality values to build-up a model to obtain the random variables of the quality indices to be used in the regulation.

Therefore, it is very important to consider the historical behavior of the distribution system to obtain the real values for the basic reliability indices:

i. the failure rate for each distribution component, segregated by the different causes that usually provoke supply interruptions: overloads, aging, lack of maintenance, storms and lightning, tree contacts, etc. and
ii. the restoration time, segregated by the type of distribution network: overhead or underground feeders.

To assess reliable values of the previous basic indices a data monitoring scheme was developed to process the rough data obtained from the distribution information systems of the regulated utilities.

On the other hand, different quality levels are required depending on the type of distribution network and the value that customers give to interruption costs. As a consequence, a methodology to segment the supplied distribution area into different zones has been developed. The two selected classifier criteria are: number of inhabitants in the municipal district and an index associated with their territorial dispersion in the zone. The quality objective values are set for each type of zone, so the comparison is made between zones of the utilities that belong to the same type.

Two types of reliability indices are controlled and compared to evaluate the quality performance of each distribution utility in each zone. First, zonal reliability indices are measured, such as SAIDI and SAIFI, they are associated to the global performance of the utility. In this case, a penalty/incentive scheme that binds the probability of reaching the objective values to the annual remuneration of the distribution utility is proposed. Second, individual reliability indices, such as number and duration of interruptions that suffer each customer, are also controlled. In this case, only a penalty that goes directly to the affected customer is applied when the utility does not meet the specific individual quality limits.

The regulatory proposal defines an implementation plan for the quality control mechanism. Usually, distribution regulation establishes annual revenues for a regulatory period of several years (four to five years). Therefore, the implementation plan considers the incorporation of new reliability data through the whole regulatory period to feedback the probabilistic model and compute new quality objective values. Hence quality improvements made by the utilities during the present period will be considered to set the objective values in the next regulatory period.

In Section 2, an overview of continuity of supply issues is presented. In Section 3, the regulatory proposal is described. In Section 4, a study case to show the implementation of the regulatory proposal is detailed. Finally, conclusions are presented in Section 5.

2 CONTINUITY OF SUPPLY REGULATION

2.1 Continuity of supply

Continuity of supply is one of the three aspects that conform power quality, along with voltage quality and commercial services [1]. Continuity of supply is related to distribution network activities, which are considered as natural monopolies and hence most regulatory schemes keep under strict control and regulation. Continuity of supply, also referred to as reliability [2,3], is measured by the number and duration of interruptions. In most countries only long interruptions are considered as continuity of supply. Long interruptions are those that last more than three minutes, the necessary time to allow automatic equipment to clear up faults. These long interruptions may be defined as permanent as well, since their occurrence will generally imply a repair action or the use of manual switchers to restore the supply.

2.2 Continuity of supply regulation

The traditional regulation of the distribution activity based on cost of service or base rate schemes is being replaced by more competitive alternatives, such as revenue or price cap schemes. These provide large incentives to cost-effectiveness that may encourage utilities to change their investments, operation and maintenance practices in order to increase their benefits. This might affect the quality performance of the distribution systems. The goals of power quality regulation are:

- i. To assure that the continuity supply levels are in accordance with the yearly remuneration of distribution utilities.
- ii. To guarantee a minimum continuity supply level to every single consumer.

It has been proposed that power quality regulation must reach the equilibrium between distribution network costs and customer outage costs [4,5]. This point of equilibrium is the so-called Optimum Quality Level. Even though the distribution network costs can be easily assessed, a problem arises when customer outage cost functions are to be computed, since the real costs of customers are unknown. Therefore it turns out to be quite impossible to deliver objective values for the required continuity of supply levels if coarse, and necessary though, simplifications are not made [6].

In this paper the authors present a regulatory proposal based on yardstick competition. Whereas the regulatory schemes that are implemented in most of the countries [1] fails in this concern. The theory presented in [4,5] do not provide a methodology to obtain the objective values of the quality indices, and the theory proposed in [6] shows many uncertainties as far as the assessment of the objective values is concerned. This proposal sets objective values for the reliability indices using a probabilistic model that takes into account the historical behavior of the distribution system. The competition is made by comparison among utilities and those pre-specified objective values, and between utilities themselves, that will try to perform better than their competitors in order not to start in an unfavorable position when new objective values will be set. This concept has been used in other cases in a different way to establish continuity objectives [7].

3 REGULATORY PROPOSAL

In this section the regulatory proposal is described in detail. First the regulatory principles whereon the proposal is based are set. Second, the regulatory scheme is presented, and finally the implementation plan is outlined.

3.1 Regulation principles

The regulatory proposal is based upon the following principles:

- i. Electricity distribution is a natural monopoly and hence has to be kept under regulation.
- ii. The continuity of supply levels are highly related to investments, operation and maintenance practices, and therefore depends on the remuneration to the distribution utility. It means that every distribution remuneration level should have associated a specific continuity supply level.
- iii. It is assumed that present continuity of supply levels correspond to the present utility remuneration. So improvements in quality levels should mean extra-revenues for the distribution utility. On the other hand, if the minimum quality level is not reached penalties should be enforced.
- iv. The competition is made by comparison among quality levels provided by utilities and pre-specified objective quality levels.
- v. The failure rate and the restoration time of distribution components are considered as random variables.
- vi. The responsibility of the distribution utility is to keep the incidence of causes that provoke interruptions under control.
- vii. The process to assess the objective values of the quality indices and the incentive-penalty mechanism must be objective, non-discriminatory and transparent.

viii. Since different quality levels are required depending on the type of distribution network and connected customers, the regulatory scheme has to propose a methodology to segment the supplied distribution area into different zones.

ix. The regulation has to be dynamic. The implementation plan should consider the incorporation of new reliability data through the whole regulatory period, to feedback the probabilistic model and compute new quality objective values for the next regulatory period. The utilities' remuneration will be reviewed as well.

3.2 Regulatory scheme

The regulatory scheme consists of four stages: zoning of the supply area, data monitoring to obtain the basic reliability indices, quality objective values assessment and the incentive/penalty mechanism. The scheme is shown in Fig.1.

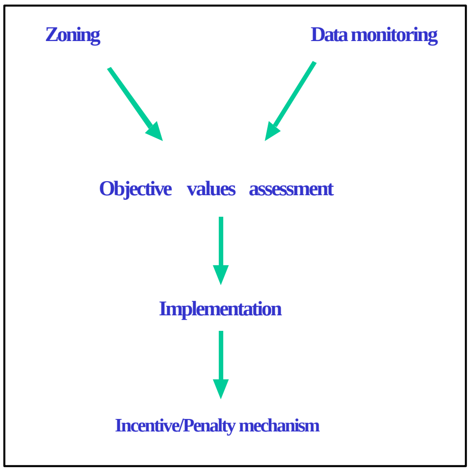

Figure 1: Regulatory scheme

3.2.1 Zoning

Since the quality level provided by utilities depends on the type of distribution network, the type of geographical area supplied and the type of consumers, it is necessary to define distribution areas types to assign them different objective values of the continuity indices. Several studies have been carried out to determine the main parameters that lead to the best definition of the different zones. The entity chosen to segregate the distribution area is the feeder. Each distribution area supplied by each feeder is classified according to two criteria:

i. The number of inhabitants in the municipal district supplied by the feeder.

ii. Their territorial dispersion assessed as the average length between medium voltage loads connected to the feeder.

The first criterion is used to classify the distribution area into the three main types: urban, semi-urban and rural. The second subdivides semi-urban and rural areas into different sub-segments (see Table 1). It has been tested that both parameters are related to reliability levels. The quality objective values are set for each type of zone, so the comparison is made between zones of the utilities that belong to the same type.

DISTRIBUTION AREA TYPES	**SEGMENTATION CRITERIA VALUES**	
	Number of inhabitants	**Dispersion (meters)**
Urban	>50.000	-
Semi-urban type1	> 5.000 and < 50.000	< 1.000
Semi-urban type2		> 1.000
Rural type 1	< 5.000	< 5.000
Rural type 2		> 5.000

Table 1: Market segments.

3.2.2 Data monitoring

A methodology has been developed to process the rough data obtained from the information systems of the distribution utilities to obtain the values of the basic reliability indices for each feeder [2,3]. The failure rate segregated by the different causes that provoke supply interruptions, such as, overloads, aging, lack of maintenance, storms and lightning, tree contacts, etc.; and the restoration time, both segregated by the type of network: overhead or underground feeders.

3.2.3 Quality objective values assessment

The algorithm to compute the quality objective values for each distribution area type consists of the following steps:

i. Once the basic reliability data have been obtained, the average and the standard deviation of the failure rate are computed for each component and each cause [8]. For each type of network, the average and the standard deviation of the restoration time are also computed [8].

ii. Simplified and schematic network schemes of each feeder for every distribution area type are defined. For each type a number of automatic breakers are assigned on intermediate points to determine the sections of the feeder. The length, for overhead and underground network, and the installed capacity for each section of the feeder are also established. A reliability model has been developed to compute the average and the standard deviation of the SAIDI and SAIFI indices segregated by causes for each feeder [2,3,8]. The reliability model considers a segregation of the restoration time. This segregation is based on the real operative sequence to restore supply to all customers.

iii. Using the Central Limit Theorem [8], the random variables of the SAIDI and SAIFI indices are obtained for each distribution area type, considering that each feeder belongs to one distribution area type.

iv. The average and percentile objective values are assessed from the expectation and the standard deviation of those random variables.

The scheme of the algorithm is shown in Figure 2.

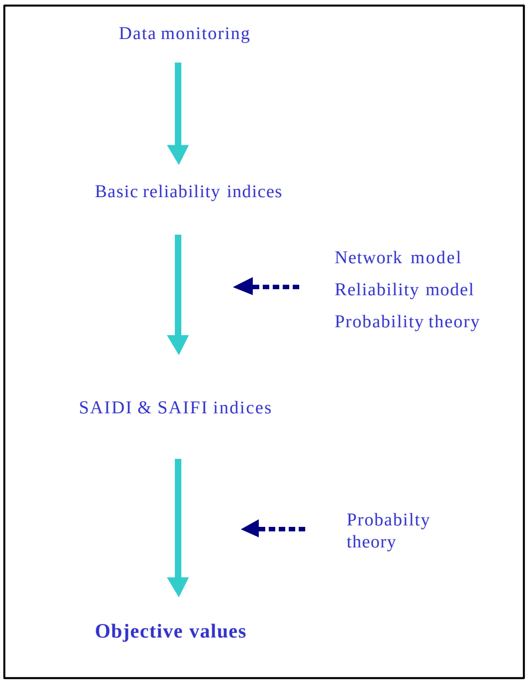

Figure 2: Algorithm scheme

The averages of SAIDI and SAIFI as objective values have an economic meaning. System quality indices are necessary to indicate that the level of remuneration is adequate. Meanwhile the percentiles of SAIDI and SAIFI objective values have a social meaning, since the supply of electricity is considered as a social right. Individual quality indices from the percentile objectives will prevent the customers from very low quality levels.

3.2.4 Incentive / penalty mechanism

Once the performance of the distribution utilities is known, the economic penalties shall be applied if the actual values of the quality indices are below the objective values. Thus the penalty scheme for the average values considers the retrieval of a percentage of the part of the remuneration of the utility that goes for quality investments. The way this percentage is assessed is relating the economic penalty to the probability of not reaching the required quality level. To define the penalty function it is necessary to take into account that those values of the quality indices that are likely to happen should be lightly penalized, while unlikely values should be heavily penalized. A function that meets these requirements is (1)

$$f(x) = \frac{x^4}{1+x^4} \qquad (1)$$

In Figure 3, the normalized distribution function of the quality random variable and the penalty function are shown. In this case the penalty function To estimate the penalty percentage it is necessary to compute the normalized version (2) of the real quality value (q) by subtracting the expected value $(m_q)$and dividing by the standard deviation (s_q), then the correspondent value for the penalty function is easily obtained.

$$Normalized\ q = \frac{q - m_q}{s_q} \qquad (2)$$

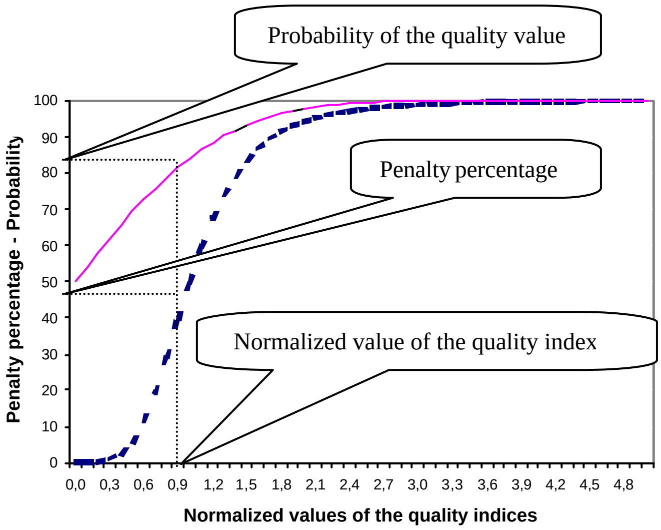

Figure 3: Penalty function (dotted line) and N(0,1) distribution function (solid line).

The penalty scheme for the individual reliability indices, which are associated to percentile objective values, considers an economic compensation to those consumers that have not received the required continuity supply level.

3.3 Practical implementation

The implementation of this regulatory scheme is based on the following principles:

i. In order to adapt the utilities to the new scheme a transition period is recommended. In the first years the regulation should emphasize on eliminating extremely low quality areas.

ii. The percentile objective value should be more demanding every year of the considered period.

iii. The penalty scheme, as stated before, should encourage distribution utilities to invest adequately.

Implementation of the regulatory proposal consists of the following preliminary steps:

i. Segmentation of the distribution area.
ii. Collect rough data to compute basic reliability indices and build up the probabilistic model.
iii. Define the duration of the regulatory period (4 to 5 years).

Once these tasks have been carried out the implementation plan continues as follows:

i. Assessment of the objective values of the quality indices (SAIFI and SAIDI).
ii. Increase the percentile objective value every year of the considered period. For instance, the first two years the required percentile could be 90%, while the third and the fourth year could be 80%.
iii. At the end of the regulatory period the new data of the interruptions that took place during the period should be used to produce new objective values of the quality indices, and a new remuneration for the utilities.

4 STUDY CASE

A study case to show the applicability of the regulatory scheme has been implemented in a large geographical area of nearly 12.000 km^2. The whole supply area has been divided into four smaller areas (namely A, B, C, and D) to simulate the competition between four distribution utilities. The zoning process has been applied to obtain the distribution area types (table 2). A four year data collection (from 1997 through 2000) was carried out to obtain the basic reliability indices (tables 3,4 and 5) and build up the random variables that will be used to obtain the objective values of the quality indices (tables 6,7 and 8.) For the sake of comparison, the objective values proposed in the Spanish regulation [9] are also presented.

ZONING (Number of feeders)				
Distribution area types	Utilities			
	A	B	C	D
Urban	12	7	0	0
Semi-urban type 1	8	3	8	9
Semi-urban type 2	2	2	9	3
Rural type 1	17	13	29	15
Rural type 2	10	8	2	10

Table 2: Results of the zoning.

RESTORATION TIME (Minutes)		
Segregation	Average	Standard deviation
Overhead network	77,0	43,3
Underground network	90,3	84,7

Table 3: Restoration time.

FAILURE RATE OVERHEAD NETWORK[1]		
Cause	Average	Standard deviation
Equipment failure	0,0291	0,0446
Storm and lighting	0,0551	0,0916
Other meteorological phenomena	0,0552	0,0975
Trees and animals	0,0076	0,0258
Aggressions	0,0033	0,0160

Table 4: Failure rate for overhead network.

FAILURE RATE UNDERGROUND NETWORK[1]		
Cause	Average	Standard deviation
Equipment failure	0,0463	0,1461
Storm and lighting	0,0029	0,0235
Other meteorological phenomena	0,0059	0,0324
Trees and animals	0,0000	0,0000
Aggressions	0,0234	0,1089

Table 5: Failure rate for underground network.

OBJECTIVE AVERAGE VALUES TIEPI (Minutes)[2]		
Area types	Proposal	Spanish regulation
Urban	61	120
Semi-urban type 1	90	240
Semi-urban type 2	185	
Rural type 1	309	480
Rural type 2	759	720

Table 6: Objective values for the TIEPI.

OBJECTIVE AVERAGE VALUES NIEPI (No. Interruptions)[2]		
Area types	Proposal	Spanish regulation
Urban	0,7	4
Semi-urban type 1	1,1	6
Semi-urban type 2	2,4	
Rural type 1	3,9	10
Rural type 2	9,7	15

Table 7: Objective values for the NIEPI.

OBJECTIVE VALUES 80 PERCENTILE TIEPI (Minutes)[2]		
Area types	Proposal	Spanish regulation
Urban	177	180
Semi-urban type 1	235	360
Semi-urban type 2	365	
Rural type 1	524	720
Rural type 2	1.211	1.080

[1] Number of interruptions per km and per year [2,3].

[2] In Spain the continuity supply indices are TIEPI (Interruption duration weighed by the installed power) and NIEPI (Number of interruptions weighed by the installed power) [9]. The difference between them and SAIDI and SAIFI lies on the fact that TIEPI and NIEPI are weighed using the installed capacity instead of the number of customers.

Table 8: Objective values for the 80 percentile of the TIEPI.

To simulate the regulation implementation these objective values were compared against the utilities performance in the year 2001. As an example, the utilities performance for the TIEPI² and NIEPI² are shown in tables 9 and 10.

UTILITIES PERFORMANCE FOR THE TIEPI (Minutes)				
Area types	Utilities			
	A	B	C	D
Urban	24	15	-	-
Semi-urban type 1	26	134	45	44
Semi-urban type 2	95	151	98	29
Rural type 1	200	197	127	309
Rural type 2	265	254	324	303

Table 9: Utilities performance for the TIEPI.

UTILITIES PERFORMANCE FOR THE NIEPI (No. Interruptions)				
Area types	Utilities			
	A	B	C	D
Urban	0,8	0,6	-	-
Semi-urban type 1	0,7	3,4	1,1	0,8
Semi-urban type 2	2,4	1,9	1,3	1,4
Rural type 1	3,5	2,9	2,2	1,8
Rural type 2	6,5	5,0	3,5	6,1

Table 10: Utilities performance for the NIEPI.

Applying the penalty function shown in figure 3 to the average values of the TIEPI and NIEPI, the resulting penalties to be enforced on the remuneration for quality investments for the year 2001 and for each utility would be:

PENALTIES PER UTILITY (%)			
A	B	C	D
0,004	3,228	0,000	0,000

Table 11: Penalties for the average values.

Different future scenarios have been envisaged to show that the implementation of the scheme shall lead to an improvement of the quality levels in the whole area and especially in those areas wherein consumers suffer from bad quality levels.

5 CONCLUSIONS

This paper presents a regulatory proposal to guarantee the quality of service provided by distribution utilities to be implemented in a regulatory environment wherein competition and cost-effectiveness between utilities are sought. This proposal gives a solution to the problem of computing quality objectives. Another advantage that presents this proposal is the way it segments the distribution area, due to the combination of two indices that are in fact related to reliability criteria. The assessment of the objective values is based on a probabilistic model built up from the historical behavior of the distribution system. The competitive environment is based on yardstick competition, wherein the competition among utilities is made by comparison of power quality levels provided by each utility against those pre-specified objective values. Although the incentive and penalty mechanism is not new, the way it relates the performance of the utilities and the quantity of the penalty is new.

A study case to show the applicability of the regulatory scheme has been analyzed.

This scheme has also turned out to be a remarkable tool to evaluate the objective performance of the distribution utilities' feeders, so it can be used to improve the investment, operation and maintenance practices of utilities.

REFERENCES

[1] Gómez T., Rivier J., "Distribution and power quality regulation under electricity competition. A comparative study", Proceedings of the Ninth International Conference on Harmonic and Quality of Power, Orlando, USA, 2000.

[2] Billinton, R., Allan, R.N., "Reliability evaluation of power systems. Second edition", Plenum Press, New York, 1996

[3] Billinton, R., Allan, R.N., "Reliability assesment of large electric power systems", Kluwer Academic Publishers, Boston, Dordrecht and Lancaster, 1988

[4] Rivier J., "Quality of service. Regulation and investment optimization" (*Calidad del servicio. Regulación y optimización de inversiones)*, Phd Thesis, Universidad Pontificia Comillas de Madrid, 2001. (In Spanish).

[5] Rivier, J., Gómez, T., "A conceptual framework for power quality regulation", Proceedings of the Ninth International Conference on Harmonic and Quality of Power, Orlando, USA, 2000.

[6] Peco , J.P., "Planning model for distribution power systems" (*Modelo de cobertura geográfica de una red de distribución de energía eléctrica*), Phd Thesis, Universidad Pontificia Comillas de Madrid, 2001. (In Spanish).

[7] Marangon L., J.W., Tanure, J.P.E.S., de Carvalho, E.B., "Quality regulation based on yardstick competition", 2001 IEEE Porto Power Conference, 10th-13th September, Porto, Portugal.

[8] DeGroot, M.H., "Probability and statistics. Second edition", Addison-Wesley Publishing Utility, 1987.

[9] Spanish Ministry of Economy. Regulation of Transmission, Distribution, Retail and Supply of the Electrical Energy. *Reglamento de Transporte, Distribución, Comercialización y Suministro de energía Eléctrica*. December 2000 (in Spanish).