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Creating a Regulatory Framework for Voltage Quality

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Abstract— **This paper provides an appraisal of what regulators need to consider in establishing an effective voltage quality regulatory framework for distribution networks. In particular, the paper considers the regulation of five voltage quality dimensions: short interruptions, voltage dips, flicker, supply voltage variation, and harmonic distortions. The paper assesses the most appropriate regulatory control method and presents practical experiences through a number of case studies.**

Keywords-voltage quality; power qualty; regulation; electricity

I. Introduction

Complementary to price, quality is an important feature of the electricity service provided to customers. Price and quality together define the value that customers derive from consuming electricity. However, electricity utilities may not necessarily be provided with a balanced set of incentives to provide both good price and quality. Strong incentives for higher efficiency and cost awareness may potentially lead to reduction of quality. Therefore, quality regulation is becoming a crucial requirement in the light of the widespread regulatory policy of (incentive based) price regulation. Quality regulation is important to provide incentives to network operators to not only become more efficient, but also to maintain or improve the quality level offered to customers.

Until now, the main focus of quality regulation has been on the reliability and commercial dimensions of quality. In contrast, there is far less experience with the issue of voltage quality regulation. Voltage quality is however becoming increasingly important to customers due to increasingly sensitive electronic devices. At the same time, voltage quality levels are in turn affected by the increased use of such devices. Thus, voltage quality deserves particular attention although being notably more complex to implement than the conventional measures of quality regulation. This is mainly due to the multi-dimensional nature of voltage quality and the inherent difficulties in measurement. Nevertheless, there is a trend of regulators becoming more aware of the need for voltage quality regulation. Steps have already been taken into that direction. This paper pursues this path and assesses the issue of what regulators should consider when establishing a voltage quality regulatory framework for distribution networks.

In a first step (section II) the paper develops a general set of guidelines that regulators should take into account when specifying the voltage quality regulation objective and the means through which to achieve this. Section III delves into five main voltage quality dimensions namely (1) short interruptions, (2) voltage dips, (3) flicker, (4) supply voltage variation, and (5) harmonic distortion. Subsequently a feasibility assessment is made, identifying the most appropriate regulatory control method. After a short excursion to existing voltage quality regulation in Europe (section IV) the conclusions of this paper are drawn in section V.

II. General Guidelines for Introducing Voltage Quality

When setting up a quality regulation framework, there are a number of crucial preconditions that need to be considered in order to make the right choices to design an effective voltage quality regulatory system. Basically it is recommended to accomplish the following three steps.

A. *Quality definition and measurements*

The first step is to clearly define voltage quality and to develop a suitable set of indicators for its measurement. It is of utmost importance that the data that feeds into the quality control is accurate since it forms the basis for the subsequent regulatory process. For this reason, also the measurement methodology needs to be defined unambiguously. Regulators can make use of existing documents such as EN5160 and the UNIPEDE “Measurement Guide for Voltage characteristics” although they will feel the need for making standards more specific.

B. *Clarify the objective of voltage quality regulation*

The second step consists of a clarification of the objective of voltage quality regulation. This can be subdivided into two intermediate steps. The first one is to quantify the existing level of performance and if possible to compare it against international best practice. The second and more challenging one is then to define a target quality level. As a matter of fact the underlying challenge is to figure out a quality level that provides highest net economic benefits since the intrinsic features of such a target are its dynamic nature (changing circumstances and customer preferences) and the trade-off between the magic triangle of costs, benefits and quality. Against this background the optimal quality level can theoretically be defined as the point at which the additional costs of providing high voltage quality are equal to the reduction in costs that customers experience due to receiving better quality.

Practically speaking, one would need to have information about the costs and benefits of quality. Notwithstanding the difficulty to obtain this information, insights can be acquired from benchmarking voltage quality levels of one network company against others or from discussions with relevant parties to identify the perceived difference between the actual and the target level of voltage quality. As a result of these assessments the regulatory objective will be to bridge the gap between the actual and the target voltage quality level. This can be achieved by pursuing either the following two policies: Improve voltage quality in case the agreed quality level is too low, or maintain the existing level in case the identified quality level sails close to the optimum.

C. *Choose suitable regulatory control method*

Once the regulator has identified the appropriate quality indicator, has robust means of measurement, and has an idea of what performance level should be achieved, the third step is to choose a suitable regulatory control method appropriate to reach that objective. To this end two crucial preconditions should be fulfilled against which the different control methods will be assessed: Firstly, the control method must lead to the achievement of the identified regulatory objective and secondly, the former must be feasible to implement. Against this background the regulator may choose from three regulatory measures:

- Performance Monitoring

The basic idea of this tool is to require the network operator to report on his voltage quality to the regulator. Subsequently this information is made available to the general public by publishing the performance of several network companies. This "naming and shaming" approach is considered as a measure to provide incentives to perform better than others due to the underlying reputation concern of the network company. The advantage of this measure is its simplicity and limited regulatory involvement. Moreover, in terms of data requirements, it can be limited to an appropriate number of strategic locations within the network thus limiting the need for extensive measuring points. The drawback of this tool however is that performance monitoring by itself does not guarantee an appropriate voltage quality as it is does not provide any concrete guidance on what voltage quality level the network operator should aim at. In case the regulator aims at maintaining existing performance levels, performance monitoring can be useful. Starting from existing levels, a decrease in performance over time will be noticed by both the regulator and customers. This can put pressure on the company to assure no further deterioration and realign quality performance with past experience.

- Minimum standards

Minimum standards dictate a minimum level (e.g. geared to EN 50160 [a] which is considered a reasonable starting point for voltage quality regulation) to be achieved for a certain performance aspect. A minimum standard provides a clear boundary on what is "good" and what is "bad" performance. In case of not meeting this standard, the utility can be penalized financially or otherwise. If the regulator aims at increasing performance, minimum standards provide clear guidelines about what quality network operators should aim at. They set quantitative targets for the companies to achieve. If combined with financial incentives for not meeting the standards, minimum standards can be very effective quality controls. In case the regulator wants quality levels to remain at existing levels, it can set the minimum standard on that basis. This again provides clear quantitative guidance in what network operators are expected to achieve. As suggested by ERGEG [7] this approach may even go further than implied by industry standards. For instance some regulators imposed quality norms based on the definitions of EN 50160 albeit with more ambitious performance targets. Moreover, so-called power quality contracts can be a solution for specific consumers who require a very high voltage quality. In this contract, customer and distributor agree on a certain performance level and additional adjustments needed to ensure that level. These costs are generally borne by the customer. In case of non-compliance, the distributor then has to pay a penalty to the latter.

- Incentive scheme

An incentive scheme can be considered as an extended minimum standard which imposes a more continuous relation between price and quality by making the financial incentive (penalty or reward) a direct function of actual performance. This makes the incentive scheme conceptually more appealing. If the regulatory objective is to improve quality, then an incentive scheme is most suitable. The gap in performance – being defined as the difference between actual and targeted performance – can be translated into a financial incentive. The better the company performs in terms of reducing the difference between actual performance and voltage quality targets, the better this is financially. By strategically configuring the level of the incentive (being the penalty or reward), incentives can be given to provide an optimal level of quality. This can be achieved by basing the incentive level on the costs that customers incur as a result of quality not being perfect. In theory, this will lead to the optimal level of quality and thus the socio-economic optimum. Incentive schemes are also very useful if one is aiming at maintaining existing levels of performance. The quality target can then be set on the basis of existing performance. But even though theoretically superior, incentive schemes have serious practical limitations. These mainly arise from two sources. First, it is difficult to exactly measure often heterogeneous customer costs due to lack of quality. In order to arrive at a sensible figure, considerable research needs to be conducted first. The second problem of incentive schemes is even more challenging: the collection of adequate and high-quality data. If actual performance is not known to a high degree of accuracy, the scheme may not be effective as the resulting financial incentive will be flawed. Good and reliable data is thus a precondition for implementing an effective incentive scheme. In order to comply with this, voltage quality meters would need to be installed – in the extreme case at the premises of each individual customer. This will clearly involve come at significant costs.

III. REGULATION OF VOLTAGE QUALITY PARAMETERS

The general set of guidelines developed in the previous section are now applied to a feasibility assessment identifying the most appropriate regulatory control method for short interruptions, voltage dips, flicker, supply voltage variation and harmonic distortions.

A. Short interruptions

Short interruptions are defined by the European standard EN 50160 as interruptions of electricity supply with a duration ranging from few tenths of seconds up to 3 minutes. These interruptions are basically accidental, and caused by a transient fault. The voltage level during a short interruption is considered to be close to zero (usually lower than 1% of nominal voltage) as indicated in Figure 1 below.

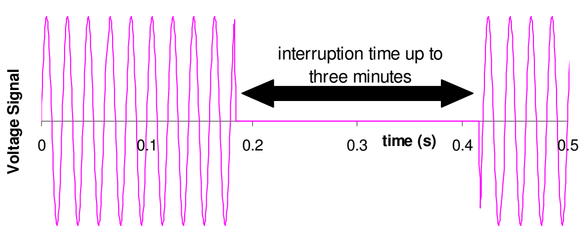

Figure 1. Example of short interruptions

An indicator which is used for reporting the frequency of short interruption is the Momentary Average Interruption Frequency Index (MAIFI), which is comparable to the System Average Interruption Frequency Index (SAIFI), but only takes into account short interruptions with duration of less than 3 minutes. MAIFI is therefore defined as:

$$MAIFI = \frac{\sum_i N_i}{N_t} \qquad (1)$$

Where:

N_i: N° of interrupted customers for interruption I (up to 3 minutes)

N_t: Total number of customers served.

The effects of a short interruption to customers are primarily perceived immediately, e.g. through immediate discontinuation of (industrial or manufactory) processes. Due to several studies on Value of Lost Load (VOLL) the interruption costs at customers increase significantly during the first seconds/minutes of a short interruption. The *monitoring* of *longer* short interruptions (1 to 3 minutes) is very much feasible, e.g. by means of manual reporting and/ or SCADA systems. However, interruptions merely lasting up to several seconds may require specific measurement systems. For these "true" short interruptions, *minimum standards* regulating the frequency of such interruptions seem to be the most appropriate quality control.

Since short interruptions are considered as one of the most important quality indicators for power supply, it is worth to consider the possibility of *incentive regulation*. For instance the approach of the Dutch regulator DTe, who included short interruptions of 1 to 3 minutes in its incentive regulation on quality, by applying SAIDI and SAIFI definitions for all interruptions with a duration of more than 1 minute has been proven feasible in the Netherlands. For interruptions lasting less than one minute this approach is however not recommended.

B. Voltage dips

Voltage dips seem somewhat similar to short interruptions, but there is one important difference. Whereas short interruptions are characterized by a voltage level close to zero i.e. less than 1% of the nominal level, voltage dips occur when voltage levels could still be relatively high i.e. typically between 1% and 90% of the nominal level, which is shown in Figure 2. Both network operators and customers can be responsible for voltage dips.

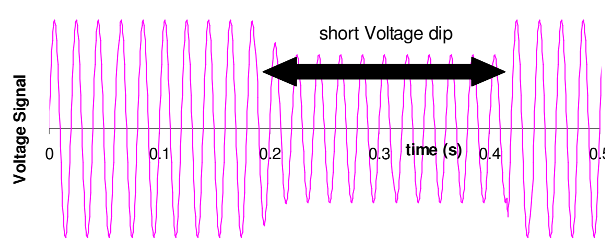

Figure 2. Example of voltage dips

The severity of both voltage dips and short interruptions is measured in terms of the duration of the event. For voltage dips, there is an additional measure needed, namely the extent of the voltage reduction.

As regards the impact on customers, the consequences of voltage dips range from 'no damage at all' to 'similar damage as (short) interruptions' depending on the depth and duration of the voltage dips and connected equipment. Short and shallow voltage dips do normally occur and in principle cannot be avoided. Deep voltage dips are very much comparable to short voltage interruptions. This implies that the damage caused by them very much depends on the duration while it grows exponentially during the first seconds/minutes.

Studies reveal that medium voltage customers are particularly sensitive to voltage dips hence regulatory control measures may be applied. *Monitoring* several classes of voltage dips should be feasible in case a voltage quality monitoring scheme will be implemented. A *minimum standard* is deemed appropriate to define the frequency of periods with a number of short and shallow voltage dips which are acceptable for both the network operator and the customer. The introduction of an *incentive scheme* may be feasible for long and deep voltage dips, but involves voltage quality measurement equipment and statistical techniques for getting a global picture of the entire network. Hence, although theoretically not impossible, incentive regulation for long and deep voltage dips suffers from some practical limitations.

C. *Flicker*

Flicker is the visual phenomenon which causes changes in the luminance of lamps and could be annoying to people above a certain threshold. Flicker is caused by rapid voltage changes and is dependent on both the amplitude of the fluctuation and the repetition rates as shown in Figure 3 below. Flicker can be characterized by the flicker severity indicators P_{LT} and P_{ST}. The indicator P_{ST} is measured over a period of 10 minutes and characterizes the likelihood that voltage fluctuations result in perceptible light flicker. The indicator P_{ST} having a value of 1.0 represents the level at which 50% of people would perceive flicker in a 60 Watt incandescent bulb. P_{LT} is calculated out of 12 successive P_{ST} values. Flicker is mainly caused by electrical equipment connected to the network by customers. However, network design and operation can reduce the effects of the distortion on the flicker perceived by (other) customers. Flicker could therefore be considered a joined responsibility of both network operators and connected customers.

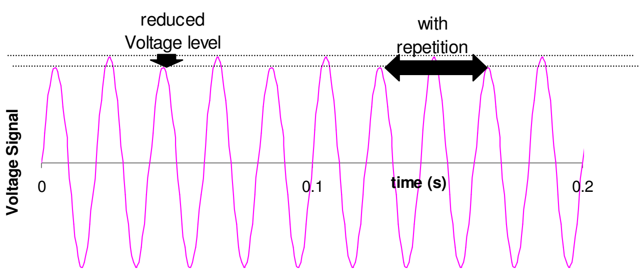

Figure 3. Example of flicker

Unlike the voltage quality parameters discussed above, flicker focuses on the impression of people rather than on malfunctioning of equipment. For this reason, flicker is mainly interfering low voltage customers. By introducing *minimum standards* for flicker severity, network operators are becoming responsible for keeping flicker within certain limits. However, at the same time, network operators should have the possibility to make disturbing customers take measures in case their disturbance leads to a non-acceptable contribution to flicker.

A first step could be *monitoring* of flicker and publication of the results. This can be realized by firstly considering the share of customers for which the minimum flicker severity standards are not met and who hence face serious discomfort due to flicker. Secondly one could introduce compensation payments on not meeting the minimum standards for P_{ST} and/ or P_{LT} for which individual customer groups may apply facing a severe discomfort from flicker. Moreover regulation could oblige the network operator to reduce the flicker level. If an *incentive mechanism* is introduced, it should be based on a decentralized, i.e. local voltage quality measure or indicator rather than a system wide measure. One could possibly consider introducing an incentive mechanism which provides incentives for reducing the number of customers for which the flicker severity standards are not met, probably using different classes of flicker severity.

D. *Supply voltage variations*

Supply voltage variations cover the variation in the voltage level under normal operating conditions. This means that they are mainly caused by changing load and generation patterns in the networks. EN 50160 defines that 95% of the 10-minutes average values of the voltage measured during a week should be within the range of ± 10% of the nominal voltage and that all 10-minutes average values should be within the range of +10%/-15% of the nominal voltage (cf. Figure 4).

Network operators can mitigate supply voltage variations by proper design and operation of the networks. Supply voltage levels are different for every node in the network. Measurement however is relatively easy. Modern voltage quality measurement devices are usually able to capture the average values for the voltage during a predefined period of time.

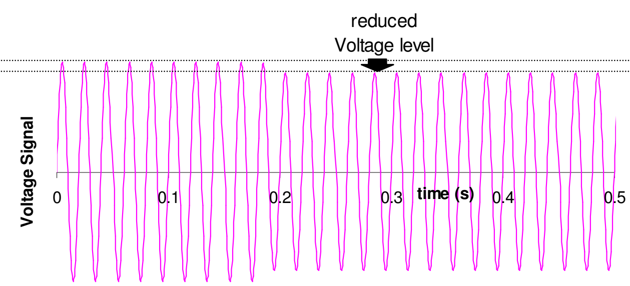

Figure 4. Example of supply voltage variation

If the standard for supply voltage variation is properly defined, the quality of 'supply voltage variation' level is either 'sufficient' or 'non-sufficient'. That is, a customer with 'sufficient' quality is most probably not prepared to pay additionally for even better quality. This is similar to flicker. As a result, *minimum standards* are widely introduced within Europe, sometimes with some adaptations from the EN 50160.

However, the introduction of a minimum standard with associated compensation payments has similar disadvantages as for flicker. The reason is that supply voltage variations could only be sensibly monitored by voltage quality monitoring devices which are not available on every connection point. Similar to the solution for flicker, we therefore suggest a solution whereby customers apply for *monitoring* if they face supply voltage variation problems. In case the voltage does not comply with the standards, network operators should pay a compensation payment and be obliged to solve the local problems. If the supply voltage meets the standards, it should be considered ‘good enough’. Against this background it is redundant to introduce an *incentive mechanism* for making ‘good enough’ quality even better.

E. Harmonic distortion

The electricity wave in Europe is based on a 50 Hz signal. Harmonic distortions come on top of the normal 50 Hz signal and are a multiple of the original frequency as illustrated by Figure 5. The individual elements of harmonic distortion are named after their multiplier. For example, the second harmonic has a frequency of 100 Hz, the third of 150 Hz and so on. The total set of harmonics is usually also summarized in the value for the Total Harmonic Distortion factor (THD), which is determined from the 2nd up to the 40th harmonic.

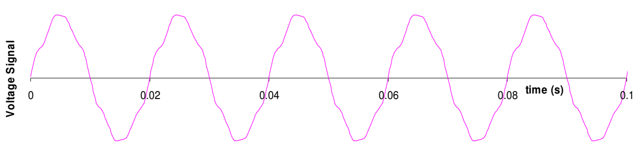

Figure 5. Example of harmonic distortion

Harmonics of the supply voltage are caused mainly by customers’ equipment. The main sources of harmonics are so-called non-linear loads which could be connected to all voltage levels of the supply system, e.g. rectifiers which are ranging from cell phone battery chargers up to railways and AC/DC converters in electricity networks. Due to the increase in non-linear loads, harmonic distortion has become increasingly significant in the last few years. In practice, most equipment is designed in such a way that it can withstand harmonic distortions as specified in EN 50160. This means that equipment will continue to operate well, will not be damaged and will be reasonably efficient. It can therefore be concluded that costs due to harmonic distortion mainly arise from harmonic distortion outside of this band. Hence *minimum standards* have been widely introduced within Europe.

Keeping these standards might not be an easy job since harmonic distortion is largely caused by customers themselves and are only influenced by network operators. However, the network operator is the only party that can coordinate the level of harmonic distortion in its network. Therefore regulation should push the network operator to keep its customers within sensible limits of harmonic distortion. In terms of *monitoring* harmonic distortion a sound monitoring program on sensibly selected nodes should be installed monitoring the share of time and/or locations where the standard has not been met. Similar to flicker and supply voltage variation this can be supplemented by compensation payments assuming that those customer groups are considered which face severe problems due to harmonic distortion.

Moreover one could think of introducing an *incentive mechanism* on a global level by applying a THD. However, since the cost curve for harmonic distortion is very asymmetric, a customer is probably not willing to pay for a better THD if his THD is only 2%, while reducing a THD of 10% could save him a lot of money. For this reason, it is probably not sensible to consider the average harmonic distortion level in a network. An incentive mechanism could therefore better focus on situation in which improvements of THD do have a value. Such an incentive scheme could concentrate on the share of time and/or locations where the standard has not been met.

IV. EXISTING VOLATAGE QUALITY REGULATION IN EUROPE

This section assesses the progress made in Norway, Italy and the Netherlands with regard to voltage quality regulation in order to obtain more practical insights into how this issue is dealt with in Europe.

A. Norway

The power industry regulator in Norway NVE put into force a new Directive on quality of supply as of 1st January 2005. The issue of voltage quality regulation is anchored in this directive in order to ensure that the quality of the electricity to customers in Norway is satisfactory, strengthens customer’s rights, and provides a better basis for handling disputes between the parties in this regard. The voltage quality regulations are set up in the form of minimum standards and are supplemented by rules for handling enquiries from connected parties to the network companies regarding quality of supply. Moreover NVE has included a provision about deviations from the standard voltage quality regulations providing for the option of bilateral agreements on voltage quality that allows for a voltage quality deviating from the minimum requirements stipulated by NVE.

The set of regulations imposed by NVE go further than the requirements on the EN 50160. E.g. the transmission system operator shall in areas that temporarily have no synchronous connections to an interconnected system, ensure that the voltage frequency is normally kept within 50 Hz ± 2 %. Moreover, network companies have to ensure that *variations in the stationary voltage RMS value* are within an interval of ± 10 % of the nominal voltage, measured as a mean value over one minute, in points of connection in the low voltage network. Furthermore, network companies have to ensure that *rapid voltage changes* do not exceed defined threshold values in points of connection,. In terms of *flicker* network companies have to guarantee that flicker severity does not exceed the predefined values. Network companies have to ensure that the degree of *voltage unbalance* does not exceed 2 % in points of connection. *Harmonic distortions* of the voltage waveform are not allowed to exceed a percentage of 8% and 5 % in points of connection with nominal voltage from and including 230 V up to and including 35 kV. Notably, for some phenomena NVE has decided not (yet) to introduce minimum standards, viz short interruptions, long interruptions, temporary overvoltages, voltage dips, interharmonic voltages, mains signalling voltage on the supply voltage and transient overvoltages.

B. Italy

Up to now the Italian energy regulator Autorità only set in place minimum quality standards e.g. for continuity of supply in order to ensure adequate service quality standards. Notwithstanding that there currently is no regulation system for voltage quality in place, the Autorità undertakes steps to establish such a system in the future. To this end the regulator's strategy is to first get a better understanding of existing voltage quality levels and to collect reliable and robust voltage quality data. As part of this the Autorità launched a voltage quality measurement campaign in early 2006 including the following main activities: installation of voltage quality meters at strategic locations and submission of data on voltage quality performance to the Autorità. As part of this effort, 400 voltage quality meters have been installed on MV busbars of HV/MV substations and 200 meters at deliver points to customers. The specifications of the meters have been developed by the Autorità on the basis of the IEC 61000-4-30 "Testing and measuring techniques – Power quality measurement methods".

The following voltage quality aspects need to be monitored and reported: Supply voltage variations, supply voltage dips and swells, voltage interruptions, voltage harmonics, flicker, supply voltage unbalance and rapid voltage changes. Moreover utilities are henceforth obliged to install voltage quality meters at the request of customers, whereas the costs of these meters are borne by the latter. Eventually customers and utilities have the possibility to enter into a voltage quality contract. The campaign will last for two years, i.e. till early 2008.

C. The Netherlands

Similar to Norway, the Dutch regulator DTe regulates different dimensions of voltage quality. *Flicker* is under regulatory control by imposing a minimum standard. For both medium voltage and low voltage networks P_{LT} limits are defined. Since network operators are obviously not the only parties who can influence flicker, the Grid Code also defines requirements on flicker for the customers connected to low voltage networks. This requirement specifies that the contribution to rapid voltage changes by a connected party on the connection point will not exceed $\Delta P_{ST} \leq 1.0$ en $\Delta P_{LT} \leq 0.8$. For *harmonic distortion* the Netherlands adopted EN 50160 limits, but added that THD $\leq$ 12% for 99.9% of time. In addition to these requirements Dutch Grid Code refers to requirements for 'producers' of harmonic disturbance.

V. CONCLUSION

Voltage quality is an important aspect of the electricity service and customers are becoming increasingly sensitive to disturbances in voltage quality. This issue is particularly important to take into account in new regulatory frameworks which put strong emphasis on cost reduction thereby potentially jeopardizing quality. Against this background the aim of this paper was to explore the issues that regulators need to consider when establishing a voltage quality regulatory framework for distribution networks.

The outcome of this paper is a set of guidelines with respect to the development of a voltage quality regulatory framework. In order to bridge the gap between the perceived and the target quality level regulators could employ different control methods to achieve their objectives, viz performance monitoring, minimum standards and incentive schemes. In theory, an incentive scheme is the most effective control as it imposes a direct link between performance and financial incentives. Although often limited by practical concerns, it still may be an interesting option for regulating especially short interruptions and voltage dips and to a lower degree flicker, supply voltage variations and harmonic distortion. In contrast, performance monitoring is practically simple to implement but lacks true incentives for increasing voltage quality. Therefore minimum standards seem to strike a good balance between performance monitoring and incentive schemes since the degree of measurement data is more restricted than under incentive schemes. At the same time, minimum standards also provide financial incentives for good voltage quality. They dictate a minimum performance and set a clear boundary of what is acceptable quality and what is not.

Voltage quality regulation is at this point in time less advanced and detailed when compared with for example regulation of continuity of supply. This can be attributed to the higher degree of complexity involved in regulating voltage quality. Nevertheless, the importance of voltage quality and therefore the need for regulation is increasing. Analysis of the issues at stake can surely contribute to a better understanding and therefore lead to effective regulatory systems. This paper can be considered as an effort in pursuing this path.

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