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Method of assessment of the state of charge and voltage level in the electric power distribution network. Implementation in the improvement of supply quality

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Abstract

Nowadays in order to know in real time the level of charge existing in a distribution network, the installation of a remote infrastructure of operation and supervision is necessary, allowing an immediate view of its electrical state, both normal operation as well as in case of incident. The analysis of the state of the network provides useful data for the adequate planning of organised maintenance, which in turn also leads to better results and serves as a basis for establishing adequate objectives of substitution or growth of the network. Nevertheless, setting this type of operation and conservation structure up in low voltage levels of distribution requires high levels of investment with lengthy repayment periods, which cannot be met by all the distribution companies. This paper proposes a low cost, short-term method of assessment of the state of charge and voltages in the distribution network, which aids the carrying out of a specific directed maintenance which in turn lowers the incident rate and provides clear objectives for improvement plans based on preventive methods. The proposed method is based principally on the details of customer invoicing, making it the ideal solution where a system of invoicing by telemetry is being used.

Keywords: Power distribution reliability; Power system measurements; Power quality

1. Introduction

The concept of quality is not a new one. It is deeply rooted in every type of industrial or service activity in our society, and is widely demanded by all sectors with different connotations.

Power Systems are not different and in some areas even, such as Production, it has been a pioneer in its internalisation and reference. In the area of distribution the concept of power quality has developed according both to customer demands and the requirements of the most widely used electrical devices and to the existing regulations [1]. It therefore becomes a "live" concept which is constantly developing and growing and that includes both the continuity of supply, wave quality and customer service.

The present trend is to regulate the first two aspects, developing regulations which protect the consumer against undesirable lacks of quality and which require the distribution companies to adopt the necessary measures so that quality levels do not exceed the limits that have been set [2–5]. In relation to customer service, although certain service patterns have been established due to its nature as a public service, its development should hopefully be subject mainly to the rules of unregulated markets and free competition.

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Traditionally, the main subject of concern for customers, distribution companies and Central Governments has been the continuity of the supply. However, the increasing number of devices with stricter supply requirements has meant that wave quality is gaining importance for customers, even residential ones, although to different extents, in such a way that at present in many countries only the existence of voltages over the limit is considered sanctionable, and then not by all the existing legislation. For this reason greater interest has been shown by the supply companies affected by these regulations in maintaining both adequate voltage levels and good rates of continuity in the supply.

The maintenance of adequate levels of continuity in supply and wave quality depends on the expansion of the criteria regarding planning, design, operation, maintenance and the extension and substitution of the distribution networks, incorporating new determining factors which must coexist alongside the purely technical and economic traditional ones. This brings with it, furthermore, the need to create a structure for the operation and supervision of the service, usually remote, which not all the distribution companies can nowadays carry out due to the level of economic investment that it requires.

Different factors exist that affect the network and influence to a considerable extent the quality of the supply, among these, apart from external factors, are those of the network itself, whose importance is fundamental and among which should be noted the age and technology, state of conservation and level of charge. While the first three are easy to obtain from existing records or inspections, the level of charge of the network varies constantly over time as a result of consumption patterns and of the existence of customers connecting to and disconnecting from the network analysed and the modification of the power contracted by them. The age of the installation, the technology of the equipment and materials used [6,7] as well as the state of conservation affect mainly the levels of continuity of the service affecting both the number of interruptions and their duration. The level of charge also affects the voltage profile at each point on the network, which, as it has been previously pointed out, is becoming increasingly relevant to customers.

The importance of the level of charge is not just this, but also the fact that it affects quite directly the average life span of the installation, its deterioration, and therefore the probability of failures in the supply.

The need of knowing the level of charge has increased as a consequence of the use of DMS and SCADA systems for monitoring, controlling and managing distribution networks. This fact has contributed to the appearance of many research works that try to evaluate the demand behaviour in low voltage distribution networks, mainly with the aim of estimating voltage profiles. The lack of measured data deals to search adequate load profile estimation techniques that start from available data such as monthly energy supplied in the area and typical load profiles for each kind of consumer. On the first hand, some works can be found in literature with the aim of improving load forecasting and thus reducing losses [8,9]. Load forecasting has been in other cases used as a base for the voltage and load estimation in real time using DSE techniques [10,11]. Other authors propose Statistical methods [12], Monte Carlo Simulations [13], Neural-Fuzzy methods [14] or Independent Component Analysis [15].

Load allocation constitutes an added target when only general data of consumption in the area is used. However, using the invoiced energy corresponding to each consumer could overcome this problem. This is the starting point of this work.

2. Proposed method for the assessment of the state of charge of distribution networks and its implementation in the improvement of the continuity of supply

The real time knowledge of the existing level of charge is subject to the implementation of a remote operation and supervision structure of the network, which allows an immediate view of the electric state of this, and its operation, both under normal circumstances and in case of incident. The analysis of the state of the network provides useful information for an adequate planning of directed maintenance which allows better results to be obtained and provides a basis for setting objectives for network substitution or growth.

Nevertheless, setting this type of operation and conservation structure up at low voltage distribution levels requires high levels of investment with lengthy repayment periods which cannot be met by all the distribution companies. This paper proposes a guiding method of assessment of the state of charge and voltages on the distribution network with low cost and short-term implementation that aids the carrying out of specific directed maintenance that in turn reduces the incident rate and provides clear objectives for improvement plans based on preventive methods.

The method is based on the allocation for each element or section of the network of a rate of use of the installation or charge capacity (RU) which reflects the state of maximum charge that it can reach and which can be defined in the following terms:

$$\mathrm{RU} = \frac{P_{\max}\ (\mathrm{kW})}{P_{\mathrm{n}}\ (\mathrm{kW})} \tag{1}$$

In which

- RU = rate of use of a unit or element of the network.
- $P_{\max}$ = maximum power demanded in a defined interval of time (kW).
- P_{n} = nominal power allocated to the corresponding element of the network (kW).

The nominal power allocated to each element of the network will depend on the temperature, type of set up, state of conservation, “age” of the installation, unforeseen happenings that it has accumulated, critical nature when faced with a power cut.

Three areas of operation can be defined for each element or section:

- Normal operation area, in which the rate of use is lower than the unit, so the power circulating is inferior or equal to the nominal allocated power.
- Non urgent operation area, in which the rate of use is above the unit and below a value defined as urgent alarm and in which the power circulating is higher than the nominal allocated power.
  In this case the operation area is of acceptable overload whose influence on the average life-span of the equipment is practically nil, the acceptable level depending both on its magnitude, duration and previous level of charge. This additional operation area for each element can be obtained by regulations or by the use of contrasted and accepted methods of calculation.
- Urgent operation area in which the rate of use is above a value defined as urgent alarm, in which the power circulating represents an overload that affects the average life-span of the element.

From the point of view of the analysis of the impact of the charge on the equipment, the operation areas of non urgent and urgent alarm clearly depend on the duration and the levels of existing charge, both during and previously, nevertheless, given the objectives set, initial data and existing conditions (low cost, short time of implementation…) they will initially be considered as independent.

If equipment exists to measure the power or intensity circulating, the rates of use or charge capacity can be obtained immediately, but this usually only occurs in medium voltage and on very few occasions in low voltage, thus making it necessary to put forward a method that allows the maximum transmitted power to be obtained in a simple way with the data existing in all electricity companies whatever their size. This data usually corresponds to invoicing and the allocation of a connection point to the network for its customers. By virtue of this allocation the list of customers supplied by a line or element can easily be obtained and, according to the invoicing, the power contracted and energy consumed by each customer can be known and for some of these customers even we could establish the maximum power consumed in a fifteen-minute period. This is the time of integration of the maximeter and it is valid for our objectives as it is lower than the thermal time constants of the majority of the elements of the distribution network.

Working from this data it is necessary to find the maximum power circulating during a fifteen-minute interval for each section of the network and for this the invoicing data base will be used, from which the energy consumed by each customer in their last invoice will be extracted and, from this, we will try to obtain the maximum power demanded, if it is not available via maximeter. It is therefore necessary to have for these customers the relation existing between energy consumed and maximum demanded power, for which we must previously carry out a customer segmentation, a sample of a sufficient number for each segment and fit them to a curve which represents this relation with sufficient accuracy. This makes it necessary to obtain for each type of customer the curve representing energy consumed-maximum power demanded, which will have at least a seasonal variation and always assuming that a variation has taken place as a result of changes in consumption habits or in the electrical devices installed. Typical exponents of what we have indicated can be found with the increase in the introduction of the night-time cheap rate or of air-conditioning units for residential customers.

Fig. 1 shows, as an example, the relationship between the maximum power demanded by a group of residential consumers connected to a Spanish distribution network and the energy demanded by them. The data correspond to January 2004, one of the months when demand peaks are reached in Spain.

Once the maximum demanded power for each customer has been obtained, estimated from a curve similar to that shown in Fig. 1, it is necessary to obtain the maximum power demanded in each section of the network for which the diversity factor DF must be found, defined as follows:

$$\mathrm{DF} = \frac{\sum P_{\max\ \text{customers}}}{P_{\max\ \text{whole}}} \tag{2}$$

where:

- DF = diversity factor.
- $P_{\max\ \text{whole}}$ = maximum power demanded by the customers as a whole (kW) in a fifteen-minute interval.
- $\sum P_{\max\ \text{customers}}$ = sum of the maximum powers demanded by each of them independently (kW) during a fifteen-minute interval.

It is therefore necessary to carry out a series of measurements to obtain the before-mentioned factor according to

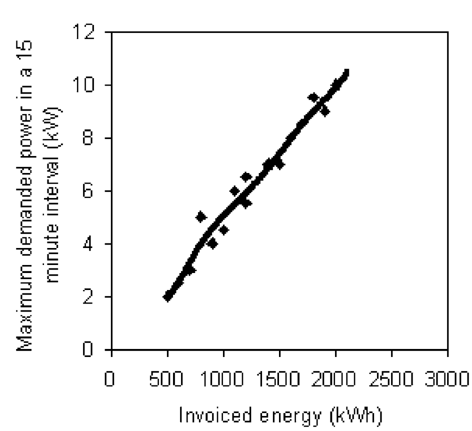

Fig. 1. Relationship between the power maximum demanded by consumers and their invoiced energy.

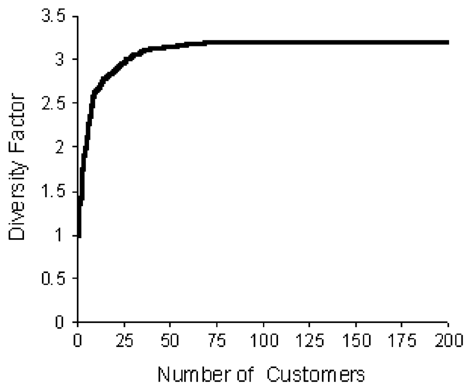

Fig. 2. Diversity factor of a distribution feeder, in function of the number of connected consumers.

the number of customers and to obtain the demand curves at various points on the network so that such diversity factors are obtained according to the number of customers. A relation between the diversity factor DF and the number of customers would be as indicated in Fig. 2. The data used for the construction of this chart have been obtained from literature [6], however, it must be pointed out that important discrepancies exist among the values of DF indicated by different authors [7,16,17], due to they are strongly influenced by the consumption patterns.

Once the curve of diversity factors for the mentioned network has been obtained and we know the number of customers supplied and the maximum power demanded by each of them, the maximum power demanded by the whole of them can be obtained from a curve in Fig. 2 or similar and therefore the rate of use of each element or section of the network (RU):

$$\mathrm{RU} = \frac{P_{\max}\ (\mathrm{kW})}{P_{\mathrm{n}}(\mathrm{kW})} = \frac{\sum P_{\max\ \ \mathrm{customers}}}{\mathrm{DF} \cdot P_{\mathrm{n}}\ (\mathrm{kW})} \tag{3}$$

By means of this later analysis of the states of charge reached at different points on the network during the invoicing period in question, we can detect possible weak points on the network, overload levels that may or may not affect the continuity of the supply, and can plan adequately preventive or corrective actions that avoid a possible increase in the likelihood of a cut in the supply at different points.

This method of calculation could obviously lead to inaccuracy in the results due to the uncertainty of some of the data, which is why they should be seen as guiding, and should be checked through later measurements, and once this is done planning can be done for directed maintenance and improvement actions based on preventive criteria.

It also presents a number of other disadvantages due to the temporary nature of the measurements, related to the periods of invoicing, obviously being inefficient in obtaining the profile of voltages at each point of the network. However, it is very simple, cheap and easy to introduce, making it an efficient tool for improving the quality of the supply mainly applicable to low voltage networks in which usually no measuring equipment has been installed that allows the state of charge in all their elements to be seen.

The improvement of this method of calculation can be based therefore on two points:

- On the one hand, knowing precisely the maximum demand.
- On the other hand, reducing the interval of measurement so that the analysed situation comes closer to the present one.

If we consider the present electric market, we can see improvement goes almost hand in hand with the new technologies of information and communication due on the one hand to the fact that the present group of energy measuring equipment, for the most part analogical, is highly obsolete, with increasing errors of measurement and in need of a progressive renovation that in many cases will be by electronic elements with digital technology capable of storing both voltage and charge curves. On the other hand, the improvement and the reduction in the prices of communications, new transmission technologies (AMR, PLC, x-DSL, WIFI...), the offer of new services, the massive introduction of wide band, etc... makes the introduction of telemetry systems related to electric energy metering systems quite feasible [18].

For this reason, following an appropriate strategy of substitution of the traditional analogical meters for electronic meters we will easily obtain a high number of charge curves enabling us to obtain in a reliable and exact way the previously indicated parameters, that is to say the maximum power for each type of customer, possible modification of consumption patterns and the development of demand, bringing even greater accuracy and simplicity to the indicated method.

The massive installation of these new types of meters will enable us to know each client's load curve, related power factor and voltage profile so that by simple superposition we will obtain for each point of the network the power demand curve of the customers as a whole supplied by this element and by means of a simple algorithm of calculation will obtain the voltage profile at each point of the network. The combined implementation of a system of telemetry means that these parameters could be obtained online and accordingly carry out the supervision of the state of charge of the network according to what has previously been explained, detecting in accordance with the resulting rates of use (RU) those charge levels that could affect the average life-span of some elements and therefore increase the probabilities of failures in these.

In short, by taking advantage of the renovation of energy measuring equipment, we would obtain the implementation of a structure of telemetry of these meters and, on the basis of the metering data, an online supervision system of the state of charge and voltages of the network with no need to install any other type of additional equipment, being especially useful for low voltage networks. The charge levels obtained in this way would be used as the basis of calculation of the corresponding rates of use and from them we would gain the necessary knowledge to carry out actions aimed at improving supply quality.

3. Application of the proposed model

As an example a little radial distribution feeder has been considered. It supplies an urban zone with a population of about 400. Its sending end corresponds to a medium voltage substation. Three transformers of 250, 100 and 50 kVA are connected to this feeder supplying 198 low voltage consumers.

First, consumers have been classified in several groups according to their consumption pattern (residential, industrial and commercial consumers). With the aim of simplifying the process, the same invoiced energy has been supposed for each consumer in the same group. Fig. 3 shows the relation between the invoiced energy and the maximum demanded power corresponding to each group of consumers. It has been obtained by metering the maximum demanded power of a sample of them and then fitting the data to an adequate curve. This stage is not necessary if consumers have a maximeter.

Maximum power demanded by each consumer can be therefore estimated from the curves in Fig. 3.

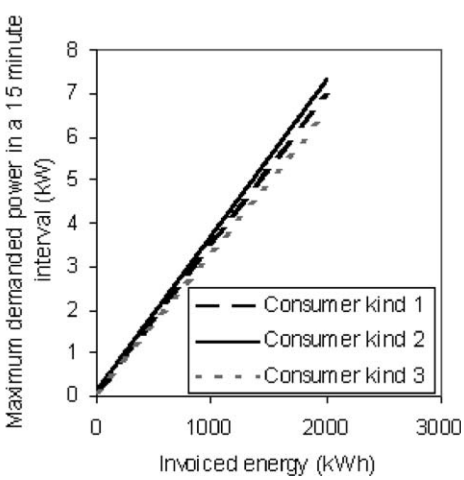

Fig. 3. Relation between maximum demanded power and invoiced energy of different groups of consumers.

Next the diversity factor for each group of consumers can be obtained from the curve in Fig. 2, or other similar one obtained from actual data of consumers in the zone under consideration. With those data, the rate of use of the different elements of the distribution feeder can be obtained from Eq. (3). The assigned power of each element is influenced by several factors like conservation, age, historical failures, etc.

Table 1 shows the nominal power of the different elements of the distribution feeder under consideration, and the ranges of rate of use whose values could be considered as non urgent operation area or urgent operation area.

The consumer classification, their connection nodes, consumption and maximum demanded powers (obtained from Fig. 3), are summarised in Table 2.

From these data and following the described process, rates of use of each element of the distribution feeder has been obtained (a power factor of 0.85 has been considered). Results are presented in Table 3.

Table 3 shows that the 50 kVA transformer is overloaded and it is working at the urgent operation area. This fact must be confirmed by metering and then corrective measures must be taken. On the other hand, the 100 kVA transformer is working at the non urgent operation area. So a monitoring of this transformer state must be only done. The rest of the feeder is working at an adequate lever, according to the results shown in Table 3. This

Table 2
Consumer data

Group of consumers	Number of consumers	Invoiced energy (kW h)	Maximeter	Maximum demanded power (kW)/consumer
250 kV A transformer				
1	40	900	No	3.17
2	15	1100	No	4.08
3	30	750	No	2.5
4	1	4000	Yes	25
4	1	2300	Yes	18
100 kV A transformer				
1	32	900	No	3.17
2	36	1100	No	4.08
3	5	750	No	2.5
50 kV A transformer				
2	38	1100	No	4.08

Table 1
Assigned power and rate of use limits for each element of the feeder

Elements	Nominal power, P_n (kV A)	Non urgent operation area (kV A)	Non urgent operation area (RU)	Urgent operation area (kV A)	Urgent operation area (RU)
First feeder section	500	525	1.05	575	1.15
Second feeder section	400	420	1.05	460	1.15
Third feeder section	250	262	1.05	287	1.15
250 kV A transformer	250	262	1.05	275	1.1
100 kV A transformer	90	95	1.05	108	1.1
50 kV A transformer	45	47	1.05	54	1.1

Table 3
Resulting rates of use of the different elements of the feeder

Element	Rate of use (RU)
First feeder section	0.53
Second feeder section	0.38
Third feeder section	0.23
250 kV A transformer	0.45
100 kV A transformer	1.07
50 kV A transformer	1.30

analysis could be easily extended to the whole distribution network in the same way.

4. Conclusions

The knowledge in real time of the state of charge of the distribution network and the profile of existing voltages, is nowadays only possible by means of the installation of a remote supervision system whose cost is not acceptable to the vast majority of distribution companies and furthermore does not reach all points of the network.

In this article an evolutionary method is proposed for obtaining the state of charge of the network and the voltages profile, reaching all its points, based on the use of invoicing data, its implementation in the improvement of supply quality by considering the factors of use of all the elements that the network is composed of and obtaining in its final state the voltage profile at each point.

The methodology described is appropriate for use in low voltage distribution networks where there is normally a great lack of measurement data, compared to high voltage networks, in which it is quite usual for the companies to have records of demand curves in their lines and to know the level of charge quite easily.

Although at first the results obtained by using the method described present a temporary nature and uncertainty related to the times of measurement and initial data which should be checked by later measurements, the use of this methodology is very promising due to the necessary substitution of the present energy meters by others that will gather data such as maximum power or demand curve, whereby the uncertainty of the data described will disappear and it will be possible to obtain the demand curve at each point on the network by simple superposition and, therefore, the corresponding rate of use of each section or unit of equipment. In these cases we certainly could consider the indicated areas of operation as a time function, which makes it very convenient for the distribution companies to introduce these types of measurement equipment, if not in a massive way, at least for a certain number of representative customers, in order to obtain in a reliable and quick way the demand curves of different kinds of customers and those existing in different sections and elements of the network, as well as knowing the modifications in consumption patterns due to changes in habits or to the introduction of new kinds of electrical devices.

All this together with the improvement and reduction of the prices of communications, new transmission technologies, the offer of new services, etc., makes the implementation of telemetry systems related to systems of electric energy invoicing quite feasible, so that the gathering of metering data could be done practically in real time and the level of charge in each element and its corresponding voltage could be obtained from these data.

With the method described we would obtain a system of supervision of the state of charge and voltage at all points of the network based on the metering system and of very low cost and simple implementation, which would provide us with reliable data for the planning of growth and improvement of supply quality.

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