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Smart Grid Voltage Control for Electrical Power Distribution System Operation Optimization

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***Abstract* - Traditional operation of distribution systems focuses on keeping user's voltage levels as close as possible to ranges around nominal values. However recent trends apply methods such as making more flexible the user's voltage level within regulatory limits to achieve optimization in distribution systems operation saving energy and obtaining other benefits including reducing CO_2 levels. This paper explores the conceptual framework of the optimization of the distribution network's operation through the use of Smart Grids technology, providing significant benefits to the operation of electrical networks in Latin America. The Colombian case is illustrated to support the conclusion of the importance to introduce new operation methods to the electrical networks in the region.**

Key words—*Conservation Voltage Reduction, CVR, Smart Grids, Voltage Var optimization, Distribution System Optimization*.

I. INTTRODUCTION

The operation of electrical systems with limitations due to power supply or capacity problems has applied in the past the reduction of energy consumption by reducing voltage and/or frequency. This practice was usually applied to critical or emergency conditions. Recently, as part of the steps to improve the energy efficiency performance of an electrical system, the reduction of the voltage supply to the minimum regulatory values is used as part of a set of interesting operation methods.

This paper presents the results of the impact analysis of voltage control to electrical networks as a policy to reduce demand during emergency conditions or permanently. This analysis deals specifically with the reduction of energy demand, although, as shown in illustrative examples, the control can be applied also to reduce the peak demand. Use cases, which are taken from recent references of Smart Grid applications in the United States of America supporting the conclusions, are presented since their features are similar to the distribution network conditions in Latin America.

II. CONCEPTUAL FRAMEWORK

A. *Conservation Voltage Reduction Factor*

It is known that dependence between power and voltage supply exist, and intuitively, this relationship is directly proportional, because to a higher voltage a higher demand and thus consumption is expected. Thereof, it is reasonable to formulate the possibility of reducing the power consumption controlling voltage levels. Besides, the load voltage supply at the load side is regulated and it is subject to limits within which the voltage must remain to provide a good quality of service. This opens the possibility of using all the supply range without affecting its quality in order to improve the global performance of the network, and particularly its efficiency reducing energy consumption. This method could have a direct impact on all the supply chain and could help to mitigate supply risks associated with a lack of energy or capacity, (peak or energy demand), particularly in critical operational conditions, and at same time minimizing CO_2 emissions.

The operational conditions of the transmission and distribution networks whose voltage levels are determined by different factors, like in the Colombian case where it is guaranteed that the energy supplied to the substations is between the normal range of ±10% of the nominal value for voltages equal to 220kV and below [1], and the connection of most final users to the distribution network make that the implementation of the voltage control measures indicated in this document are limited to those called distribution networks, and particularly those with a radial characteristic. In this case, the ring main electrical power distribution systems are excluded even if they have voltage levels below as mentioned.

The relationship between tension reduction and power reduction is known in the technical literature as Conservation Voltage Reduction (CVR). The principle of CVR suggests that if the voltage is reduced at the customer metering point at the lower-end but within the allowed band, electric energy (kWh) could be saved. Reductions in peak demand (kW) and losses are also additional benefits in some applications [2].

Effectiveness of CVR is evaluated by the "three" Conservation Voltage Reduction factor (CVR_f), one each for power (kW), reactive power (kVAR) and energy (kWh), respectively. It is defined as the percentage reduction of the quantities resulting from 1% reduction in voltage [2].

$$CVR_f = \frac{\%\, Reduction\ of\ Quantities}{\%\, Voltage\ Reduction} \quad (1)$$

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B. Load Characteristic and its relation the CVR Factor

In general, loads can be modeled as constant impedance, constant current or constant power loads, however, realistic load models are a combination betwen the diferents kinds of loads, assigning a percentage of the total load to each of the components [3]. This behavior is represented by the ZIP model [4], which relates the apparent power as a quadratic voltage function, where the coefficients are constant impedance (Z), constant current (I) and constant power (PQ). In some cases these coefficients can assume negative values as verified in laboratory tests [3].

$$S = S_0\left(Z*\left(\frac{V}{V_0}\right)^2 + I*\left(\frac{V}{V_0}\right) + PQ\right) \tag{2}$$

Where:

S: is the actual apparent power;
S_0: is the apparent power at a reference voltage V_0
(Z + I + PQ) = 1 [4].

A particular case is when Z=1, case that corresponds to a 100% constant impedance load model (e.g. resistive load), which has been representative of a large number of residential consumer loads in Latin America. Under this assumption, it is possible to define an approximate value of the CVR factor as follows:

$$S = S_0\left(1*\left(\frac{V}{V_0}\right)^2\right) \qquad S = \frac{V_0^2}{Z}*\frac{V^2}{V_0^2} \qquad delta\,S = \frac{2V^2}{Z}\,\frac{delta\,V}{V}$$

$$\frac{delta\,S}{S} = 2\,\frac{delta\,V}{V} \tag{3}$$

Where:

S: apparent power; V: Voltage

Equation 3 shows that the ratio of power variation is two to one with respect to the voltage variation, i.e. for a 1% reduction in voltage, the apparent power can be reduced by 2% (CVR Factor = 2).

Typical ZIP values were identified in the United States as 30% Z and 70% PQ for a residential, 50% Z and 50% PQ for commercial and 20% Z and 80% PQ for industrial customers [5]. Some load factors measured for end users appliances are presented in Table 1.

TABLE 1. ZIP VALUES FOR END-USE LOADS [6]

Device	Z%	I%	PQ%
FAN	73	25	2
Sony Plasma TV	-32	48	84
LED TV Med Quality	-45	45	100
CFL 13 W	40	0	60
Incandescent 75 W	58	42	0

In addition it is important to study the changes of load characteristics due to technology changes, since sometimes some characteristics of emerging loads do not imply higher CVR values, and in some cases they show inverse behavior (Fig. 1) [7]. This confirms that the types of loads on a feeder have a direct impact on the potential benefits of CVR, therefore it is important to determine, for the distribution system, the CVR factors that characterize it, which depend on the mix of different load kinds served.

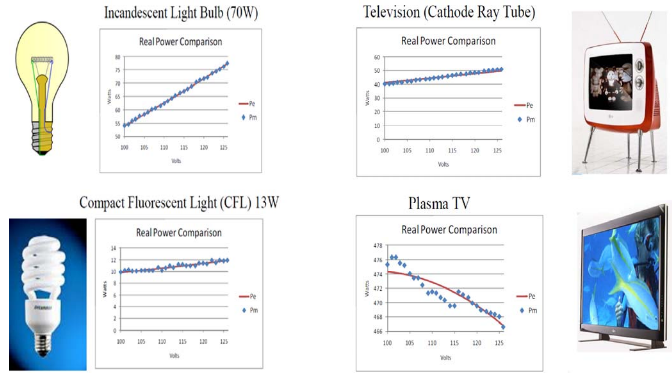

Fig. 1. Behavior's characteristics of emerging loads [7].

What makes it more difficult to make an accurate assessment of the energy savings by CVR is that the load composition is not known for most of the feeders, and it changes with time.

C. Other aspects to consider

Another important element to be taken into account is the behavior of demand throughout the day. Load variations are reflected in the voltage profiles of feeders, increasing its voltage drops when the energy consumption is higher. Fig. 2 shows the hypothetical voltage profile of a feeder that connects directly the transformer with the load for two different demand conditions, during peak hours and during off-peak hours, and applying Conservation Voltage Reduction methods (V objective: 0.9 p.u.) and another without applying the CVR (V objective: 0.95 p.u.).

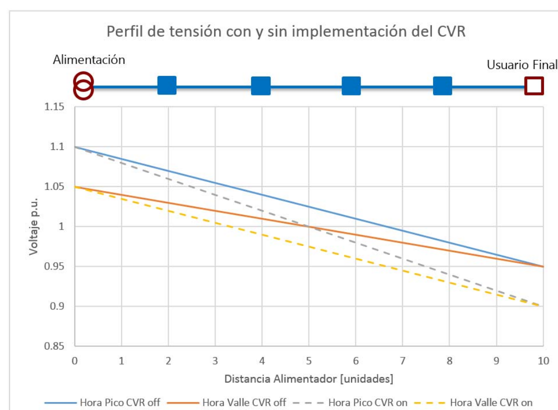

Fig. 2. Hypothetical voltage profile of a traditional feeder

Fig. 2 assumes that there are no intermediate devices that improve the voltage profile. This behavior is typical in electrical distribution networks in Latin American countries, where it is unusual to find a significant deployment of intermediate devices such as voltage regulators or even capacitor banks [10].

Considering the presence of intermediate devices that influence the voltage profile the expected result is more likely the one shown in Fig. 3.

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As a result, it is noted that with the implementation of voltage control means it is possible to use the entire voltage range defined in the regulation with benefits for the energy efficiency of the supply, provided the CVR factor is appropriate. The following questions need to be responded before the implementation of methods applying CVR:

- Is the CVR factor attractive to implement voltage control?
- What is the voltage range in order to reach the regulatory limits at the end of the feeder?
- If both above answers are yes, how can this functionality be implemented in the short term? At what cost?

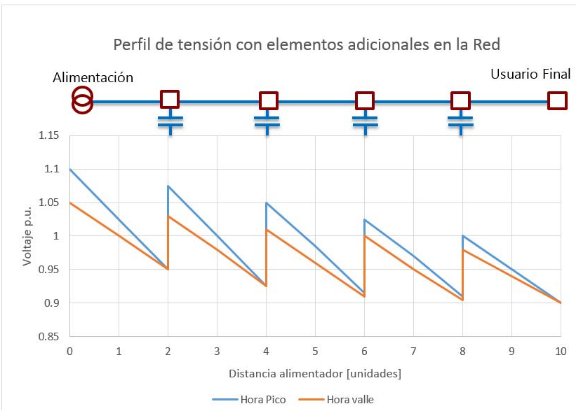

Fig. 3. Hypothetical voltage profile of a feeder with capacitor Banks

III. CVR Implementation for Energy Consumption and Peak Demand Reduction

A. Implementation in distribution systems

Voltage control as a means to search for energy efficiency is key according to the approaches of the United States Department of Energy (DOE), which identifies the CVR functionality as one of the 6 main areas of focus to ensure energy efficiency in distribution systems [11].

It is important to highlight that DOE complements this function with policies for the implementation of smart metering and automation of the distribution networks, important features to ensure compliance with regulatory limits, issues that are also identified in other references such as the Colombia Smart Grid Roadmap developed with IDB support [8].

The development of this function in the United States has been important because the ANSI Standard C84.1 [2006] stipulates that under normal operating conditions the voltage at the customer premise must be limited to ±5% of its nominal value. In other words, the voltage must be within 114V-126V for a 120V system[12]. This band could be compressed to the lower half (114-120) [2].

Decades of field research in US have defined that in a large portion of the distribution networks for each 1% reduction in the operating voltage, the average energy consumption for residential and commercial loads are reduced by approximately 0.8% [2]. However, the factors vary widely from one substation to another, from feeder to feeder and particularly from load to load.

B. Use of coordination central systems

In order to achieve a more reliable, safe and affordable electricity system, utilities have directed efforts to develop interoperability and improve the efficiency of the fundamental elements of the network. For distribution system optimization, some technologies are integrated to support network efficiency and resilience in a changing environment. An example of this integration is the deployment of a *Voltage Var Optimization (VVO)* scheme, which seeks to develop and implement an optimal switching plan, coordinated with all control devices available in the system (Fig. 4) [9].

This is an indication that in order to obtain all the expected benefits, it is important to have control systems with applications that optimize the coordination of the devices involved supported by SCADA, in oreder to align its operation with objectives such as energy efficiency.

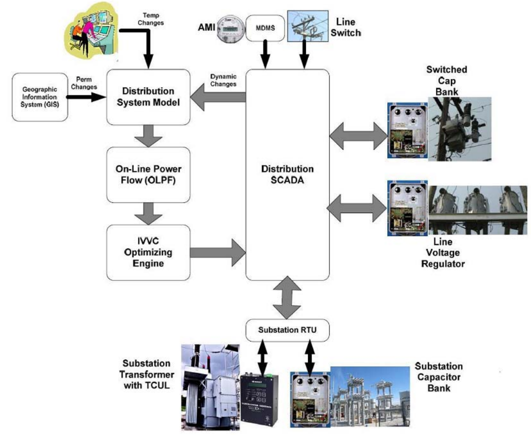

Fig. 4. DMS model based VVC (details of IVVC control components [9]

IV. CVR Implementation - Colombian Case

For the case of Latin American electrical systems, in the absence of experimental values, it is reasonable to assume that the CVR factor value is larger than those reported for the US, since loads are mostly residential in developing countries. In this respect the expected value of CVR for the Colombian case is between 1 and 2.

A. Regulatory Framework

The regulatory CREG 070 Resolution of 1998, which was subsequently amended by Resolution CREG 024 of 2005, establishes the allowable range for frequency and stationary voltage's magnitude variations in the Colombian electrical grid. In this regard, Annex I of the Resolution 024 establishes that at 60 Hz the steady state voltage may not be less than 90% of the nominal voltage nor can exceed 110% of nominal for a period of time longer than one minute. Such variation intervals are also established in the Colombian Technical Standard - NTC 1340 2004. [1]

Additionally, Colombian regulatory framework considers the decrease the power consumption as a result of voltage and frequency values reduction. In effect, the general Annex of the

Operation Code (Res. CREG 025 of 1995), defines the Energy Reliability Limit as: "*the maximum acceptable level of risk to supply energy demand. This level of risk is measured with the VERE index ("Valor Esperado de Racionamiento de Energía"), which is expressed as a percentage of the monthly energy demand and has a value of 1.5%, obtained as the maximum possible reduction in energy demand by reducing voltage and frequency, without causing disconnection of circuits.*

These definitions recognize the possibility of energy saving as a result of voltage reduction.

B. Analysis

An analysis of the implementation of the CVR in the Colombian electric grid indicates that it is necessary to consider the following key aspects:

- The deployment of the CVR technology should focus on distribution networks, especially those with radial configuration because it is there where most users are connected and where the impact of this technology may be higher. A list of typical feeders in Colombia is available in [10].
- Energy savings will not take place in the entire energy demand, only on the energy reaching distribution systems, which for the Colombian case is estimated to be in the range of 60% to 75% of the total demand.
- The distribution systems operators have little knowledge of the configuration and the actual state of their networks. It is considered necessary to determine the detailed modeling of the circuits with the purpose of determining easily and effectively the CVR Factor of each one, both for energy and peak demand; this will allow to evaluate the expected results for each of the circuits where voltage reduction actions are applied.
- Colombian distribution networks do have limited voltage regulation equipment and they have very few capacitors banks and switching elements. In some cases, the only available element to control the voltage level is the "tap changer" of the power transformer, which in many instances can not be operate under-load.
- Many of the distribution circuits are mixed, that is they supply residential and commercial loads simultaneously and at the same time urban or rural areas including hospitals and other critical load centers. This condition makes more difficult to calculate the CVR factors and to define a minimum operating voltage value. It is considered necessary, to analyze the need of distribution circuits reconfiguration and to improve the planning of future circuits, with the objective of unifying the criteria to prepare the network for CVR and distributed generation incorporation.
- Several feeders of the Colombian distribution system are characterized by their length, reach more than 50 Km even at medium voltage levels (13.2 kV) serving rural areas. Because of this characteristic, they can not be included in CVR programs, since they have little or no margin to vary the voltage without affecting users while respecting the regulatory limits [10]. In all these cases field tests should be take place to verify desk analysis and voltage measurements at end points shall be implemented to make sure that voltage quality is not affected.

V. CONCLUTIONS

As discussed in this document it is reasonable to assume that the expected CVR factor in Latin America electrical distribution networks supports the savings of at least 1% in energy consumption, reaching in some cases up to 2%, for each 1% voltage reduction.

The percentage of the total load of a country supplied by distribution circuits, which could be the target of the demand impacted by CVR, is between 60% and 75% in the case of Colombia.

In consequence with a conservative value of the CVR factor, based on the reported CVR values of the United States (close to 1), an estimated energy savings close to 3% of total demand is expected when a voltage reduction plan of about 5% is applied in the Colombian case. This could be a significant contribution to energy consumption reduction in particular during critical operating conditions.

However, because of the lack of automation and voltage control devices available on the network, it is convenient to analyze the implementation of CVR in detail in order to achieve both temporary and permanent effects, since the measures taken could be adopted, after the analysis and evaluation of the obtained results, to the normal operation, bringing benefits for the whole sector including users who should see reflected these consumption savings in their bills.

REFERENCES

[1] ICONTEC,"NTC 1340: Electrotecnia. Tensiones y frecuencia nominales en sistemas de energía eléctrica en redes de servicio público", 2013.

[2] NRECA-DOE Smart Grid Demonstration Project "Costs and Benefits of CVR Warrants Careful Examination", 2013 http://www.nreca.coop/wpcontent/uploads/2014/01/NRECA_DOE_Costs_Benefits_of_CVR_b.pdf

[3] William H. Kersting. "Distribution System Modeling and Analysis". New Mexico state University. CRC Press ISBN 0-8493-0812-7

[4] Prabha Kundur, Power System Stability and Control.: McGraw-Hill Inc,1993.

[5] Greg Shirek, "Evaluating Conservation Voltage Reduction with Windmil," Milsoft Inc., 2011.

[6] Pacific Northwest National Laboratory, Greg Shirek, "Evaluating Conservation Voltage Reduction with Windmil," , 2011, http://www.pnnl.gov/

[7] Bob Uluski (EPRI), "SMART DISTRIBUTION APPLICATIONS &THEIR INTEGRATION IN A SMART GRID ENVIRONMENT", IEEE PES General Meeting, 2011

[8] Andres Llombart - Circe, "Propuesta de Hoja de Ruta para la Implementación de Redes Inteligentes en Colombia", Congreso CNO, Cartagena, Noviembre 2015.

[9] R. Uluski, "VVC in the Smart Grid era," Power and Energy Society General Meeting,, pp. 1-7, 2010.

[10] Keraunos, "Identificación y Análisis de los niveles de calidad del servicio alcanzables en las redes de distribución del SIN", Informe Final, Estudio contratado por la CREG, Diciembre 2013.

[11] Department of Energy USA, "Energy Efficiency in Distribution Systems", DOE/Recipient Forum, 2011.

[12] Voltage Ratings for Electric Power Systems and Equipment (60Hz), ANSI Std. No. C84.1-2006,New York.