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INGENIERÍA ELÉCTRICA

Análisis cualitativo del impacto de la respuesta de la demanda en los cargos por uso del sistema de distribución

ELECTRIC ENGINEERING

Qualitative analysis for demand response impact on distribution system rates

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Resumen

Los sistemas eléctricos enfrentan grandes demandas de electricidad durante cortos periodos debido a los hábitos de consumo de los usuarios. En estos periodos, la operación del sistema de distribución es costosa, se incrementan las pérdidas de energía y disminuyen las tensiones en los nodos retirados de los alimentadores. Una forma de evitar estos efectos negativos es la Respuesta de la Demanda (RD). Actualmente se adelantan políticas que pretenden estimular la RD en Colombia, y resulta fundamental establecer criterios que permitan predecir el impacto que tendría en el mercado eléctrico. Este trabajo tiene como objetivos clasificar e identificar el impacto que podría tener la RD en los cargos por uso del sistema de distribución. Los resultados muestran que, bajo el actual esquema tarifario, es posible clasificar el impacto de la RD sobre estos cargos en cinco aspectos: Capacidad de equipos, ventas de energía, pérdidas de energía, pagos entre operadores de red y calidad del servicio. Finalmente, se identifican y clasifican aquellos parámetros que hacen parte de la metodología del cálculo de cargos por uso del sistema de distribución que son sensibles a la RD según la regulación vigente.

Palabras clave: *Cargos por Uso del Sistema de Distribución, fórmula tarifaria general, respuesta de la demanda.*

Abstract

Electric power systems are subject to high electricity demand variations during short periods due to consumption habits of end-users. In these periods, the operation of distribution networks is expensive, energy losses are increased and voltages may drop for buses located far from feeders. These negative effects can be avoided when Demand Response (DR) schemes are considered. Currently, policies for promoting DR in Colombia rise and it is fundamental the establishment of criteria for identifying the impact of DR in Colombian electricity market. This work tends to classify and identify the impact of DR on Usage Costs of Distribution Systems. Based on the current rate scheme, results show that this impact can be classified in five aspects: equipment capacity, energy sales, energy losses, payments between network operators and energy service quality. Finally, parameters of current methodology for the calculation of Usage Costs that are sensitive to DR are identified and classified.

Keywords: *Demand response, general rate formula, Usage Cost of Distribution System.*

1. Introduction

DR is defined as the ability of an energy consumer of reducing its electricity demand in response to a market signal (Marulanda et al., 2014). Several countries around the world have applied DR and have achieved positive results, as pointed in different reports. In 2015, a report from Federal Energy Regulatory Commission – FERC (United States Federal Energy Regulatory Commission) (2015) indicates that DR has the potential of reducing the electric energy peak consumption in a 6.2% of the peak demand (near to 29,000 MW); additionally, a considerable growth of subscriptions to DR programs has been reported from 2012 to 2013, with increases of 60% for incentive-based programs and 70% for usage-time-based programs.

On the other hand, European countries such as France and Switzerland have also reported advances related to DR (Smart Energy Demand Coalition, 2015). French market has a maximum contracted capacity of 5000 MW in demand resources distributed in frequency control programs and ancillary services, offering incentives from 10 €/MWh to 400 €/MWh (which are rarely paid), according to the subscribed DR program. In contrast, Switzerland market has achieved a reduction capacity up to 1150 MW offering incentives and penalties in the DR programs. In this case, the offered incentives for consumption reduction vary between 4.89 CHF/MW/h and 28.28 CHF/MW/h according to the program. In this case, penalties for breach of obligations are determined instead according to the responsibility of the energy service provider.

Finally in South America, efforts are focused in the development of regulatory policies that incentives DR programs. The Agência Nacional de Energia Eletrica - ANEEL (Regulatory agency of Brazilian electric network) issued the resolution no. 464 of 2011 with the purpose of sending economic signals to small users connected to low voltage networks by means of the energy rate. In this case, three different prices are offered during the day related to the consumption level, i.e., higher prices are offered during peak-demand hours, lower prices for low consumption hours and intermediate prices for the remaining hours (Bueno et al., 2013). Similarly, Colombia is also interested in the stimulation of DR programs for Colombian power network. By means of law 1715 of 2014 (submitted by Colombian Congress, Congreso de Colombia, 2014), it was clear that there is an interest of Colombian National Government for promoting policies of DR, delegating the establishment of the corresponding regulating mechanisms to Comisión de Regulación de Energía y Gas – CREG (Colombian Commission for Regulation of Energy and Gas). Additionally, in this document, the Programa de Uso Racional y Eficiente de la Energía Eléctrica - PROURE (Program for Rational and Efficient Use of Energy) and other forms of unconventional energy resources is defined as the instrument for the promotion and funding of DR proposes. On the other hand, the Ministerio de Minas y Energía (Colombian Mining and Energy Ministry) issues the decree 2492 of 2014 (Ministerio de Minas y Energía, 2014) that dictates the guidelines for CREG to promote the efficient energy management and DR. These guidelines include hourly rates that allow end-users to receive hourly signals through the rate formula.

Specifically in Colombia, the General Rate Formula contains costs associated to generation, transmission and distribution of electric energy in the country. Due to DR directly affects to end-users, retailers and Network Operators (OR in Spanish) will receive the first signals of the required adjustments of rates. Now, a detailed recompilation of current regulatory framework is also required in order to develop a numerical analysis that may indicate the modifications to the rate; this recompilation and numerical analysis will allow the identification of General Rate Formula parameters that require an adjustment for the new conditions imposed by DR. This research intends to contribute in this revision and give qualitative indicators of variations that an OR and/or retailer is subject for the Usage Cost of Distribution System considering DR. Quantitative analysis is proposed for further researches.

The remaining sections of this paper are organized as follows: section 1.1 presents general concepts related to DR; section 1.2 presents the General Formula Rate for calculation of electricity cost for regulated end-users. On the other hand, section 2 presents the methodology for the calculation of Usage Cost of Distribution System and the possible impacts of DR on this cost. Later, section 3 presents a summary of the classification of the impact of DR on Usage Cost of Distribution System, that is, the results and discussion. Final section features the main conclusions obtained from this work.

1.1. Basic concepts of demand response

DR is defined as the modification of end-user energy consumption habits due to a response to variations on the electricity price in real-time or the application of incentive payments designed for inducing a reduction in electricity usage when prices are high or power system reliability is at risk (Federal Energy Regulatory Commission, 2012). From this definition, a Demand Response Program (DRP) is the set of rules, agreed between participants and service providers, related to the methods used by participants to manage their consumption and how service providers are committed to this management. These programs are offered by Curtailment Service Providers (CSP), which act in the market as representatives of the end-users subscribed to their program (Marulanda, 2014).

End-users can participate in a DRP if they are capable of voluntarily modifying their consumption habits and/or they allow a remote demand variation by CSPs. In general, an end-user can modify its consumption using one of these strategies (Ruilong et al., 2015):

Reducing electricity consumption during high demand periods, with no change during other periods

Recharging energy storage devices during low demand periods

Moving its own consumption from high demand periods to low demand periods

Although effects of DR in a power system depend mainly of the programs that end-users participate, it is evident that DR directly affects operating costs along the power system. For example, demand reduction during peak-consumption hours may reduce transmission network congestion, which leads to a better use of lower-cost energetic resources for generation; additionally, this reduction obtained from active participation of DRP users leads to a reduction of power system losses and its respective costs, as power flow through lines is also diminished. Finally, end-users could also obtain a lower electricity rate (Siano, 2014).

The purpose of this work is to identify the effects of DRP implementation on costs associated to transportation of electric energy through Colombian distribution networks, from a review of current Colombian regulation. These costs are paid by means of Usage Costs of Local Distribution System (SDL in Spanish), which are also a part of the General Rate Formula to be described next.

1.2. General Rate Formula for the calculation of cost of provision of energy service to regulated users in the colombian National Interconnected System

In 2007, CREG established the General Rate Formula that retailers of colombian National Interconnected System (SIN in Spanish) must apply to calculate the costs of provision of energy service to regulated users (CREG, 2007). This rate system seeks prices that approximate to a competitive market, preventing the assignment of costs for inefficient management of retailers to end-users (Congreso de Colombia, 1994).

The General Rate Formula is based in the calculation of the unitary cost of lending service, which features variable costs and fixed costs (CREG, 2014a). The former reflects the base rate of commercialization, while the latter depends on the consumption level. According to this, variable costs are expressed in Colombian pesos (COP) per kWh and fixed costs are expressed in COP per bill. Actually, fixed costs are set to zero. The variable cost component is calculated according to (1) (CREG, 2014a):

$$CUv_{n,m,i,j} = G_{m,i,j} + T_m + D_{n,m} + Cv_{m,i,j} + PR_{n,m,i,j} + R_{m,i} \quad (1)$$

where:

n Voltage level at which end-user is connected

m Month of calculation for unitary cost of lending service

i Retailer

j Commercialization market

$CUv_{n,m,i,j}$ Variable component of unitary cost of lending service for end-users connected to voltage level *n*, corresponding to month *m*, of retailer *i*, in commercialization market *j*

$G_{m,i,j}$ Cost of energy purchase during month *m*, of retailer *i*, in commercialization market *j*

T_m Usage Cost of National Transmission System (STN in Spanish) during month *m*

$D_{n,m}$ Usage Cost of Distribution System corresponding to voltage level *n*, during month *m*

$Cv_{m,i,j}$ Commercialization margin during month *m*, of minor retailer *i*, in commercialization market *j*

$PR_{n,m,i,j}$ Cost of purchase, transportation and reduction of energy losses accumulated to voltage level *n*, corresponding to month *m*, of retailer *i*, in commercialization market *j*

$R_{m,i}$ Costs of restrictions and services associated to generation assigned to retailer *i* during month *m*.

This works aims to the qualitative determination of a DRP impact in Usage Cost of Distribution Systems. For this purpose, a detailed description of possible variations of after implementation of DRP is required under current regulation; quantitative analysis is considered as a future work. Additional detailed of the remaining terms of (1) can be reviewed in CREG (2007) y CREG (2014a).

2.Methodology

2.1. Usage Cost of Distribution Systems

The methodology for calculation of Usage Costs of Distribution Systems is established by CREG. According to the current regulation (CREG, 2008a), these costs are determined based on the operating voltage levels of Regional Transmission Systems (STR in Spanish) and SDL, identifying four voltage levels:

Level 4: Systems of a rated voltage greater or equal to 57.5 kV and lower to 220 kV

Level 3: Systems of a rated voltage greater or equal to 30 kV and lower to 57.5 kV

Level 2: Systems of a rated voltage greater or equal to 1 kV and lower to 30 kV

Level 1: Systems of a rated voltage lower than 1 kV

From a revision of these calculations for each voltage level, five aspects that DR may affect were identified:

Aspect 1 (A1): a reduction of peak demand or load displacement, decrease the number and/or the capacity of new equipment to be installed. This affects management, operation and maintenance costs, land cost and investments associated to electric assets and other costs based on constructive units.

Aspect 2 (A2): a demand reduction decrease incomes for energy sales obtained by retailers. This does not apply for DRP that incentives consumption relocation for regulated users, due to current regulation established only one energy cost along the day, therefore, consumption relocation would not reduce the net income of retailers.

Aspect 3 (A3): a reduction or relocation of demand during peak-demand hours could reduce daily energy losses, which would affect short-term purchases and sales of energy between OR, while long-term losses recognized by CREG might be affected as well.

Aspect 4 (A4): variation of consumption habits of end-users leads to modifications on power flow distribution among different OR, causing modifications on liquidations of energy imports and exports between them. Similar to previous aspect, DR would affect short-term purchases and sales of energy between OR.

Aspect 5 (A5): a demand reduction during peak-consumption hours allows an ample operation, i.e., decrease the probability of exceeding technical operating limits of power system elements. Additionally, DRP offer extra resources to OR that would guarantee a safe operation of the power system. This could also reduce the number and duration of interruptions associated to equipment overload.

The featured aspects will be applied to classify the impact of DR in every parameter of Usage Cost of Distribution Systems in Colombia. These parameters will be described for each voltage level in the following sections. On the other hand, it is important to highlight that a new resolution propose is currently under enquiry, which could modify the methodology used for calculation of Usage Cost of Distribution Systems (CREG, 2014b). This work is presented as a contribution for the construction of a novel methodology for this calculation that features the effect of DRP implementations in Colombian electric system.

2.2. Usage Cost of Distribution Systems for voltage levels 2, 3 y 4

Currently, the Usage Cost of Distribution Systems for a retailer with activities in voltage levels 2, 3 and 4, i.e., the value for , is calculated according to (2) (CREG, 2008a; CREG, 2008b):

$$Dt_{j,n,m} = \frac{CD_{4,R,m}}{1\text{-}PR_{n,j}} + CD_{j,n,m} + \Delta Dt_{j,n,m} \qquad (2)$$

where:

n Voltage level for user connection (2, 3 or 4)

$Dt_{j,n,m}$ Usage Cost for voltage level n of STR R (if n=4) or OR j (if 1<n <4), for month m.

$CD4_{j,n,m}$ Cost of voltage level 4, of STR R, for month m.

$CD_{j,n,m}$ Maximum cost for voltage level n, for month m and OR j. This parameter is equal to zero for calculation on voltage level 4.

$PR_{j,n}$ Factor for referring energy measures from voltage level n to STN, in the power system of OR j.

$\Delta Dt_{j,n,m}$ Incentive for a three-month variation of energy quality of OR j during month m, applicable to Usage Cost of voltage level n. This parameter is equal to zero when calculations are performed for voltage level 4.

Costs associated to voltage level 1 are presented in section 2.3. Each parameter featured in Eq. (2) depends on other parameters, which might be susceptible to DRP implementations. Figure 1 shows a diagram with the parameters that affect the calculation of Usage Costs of Distribution Systems in voltage levels 2, 3 and 4 and how these parameters are related to each other. The following sections will contain details related to the calculation of parameters of Figure 1.

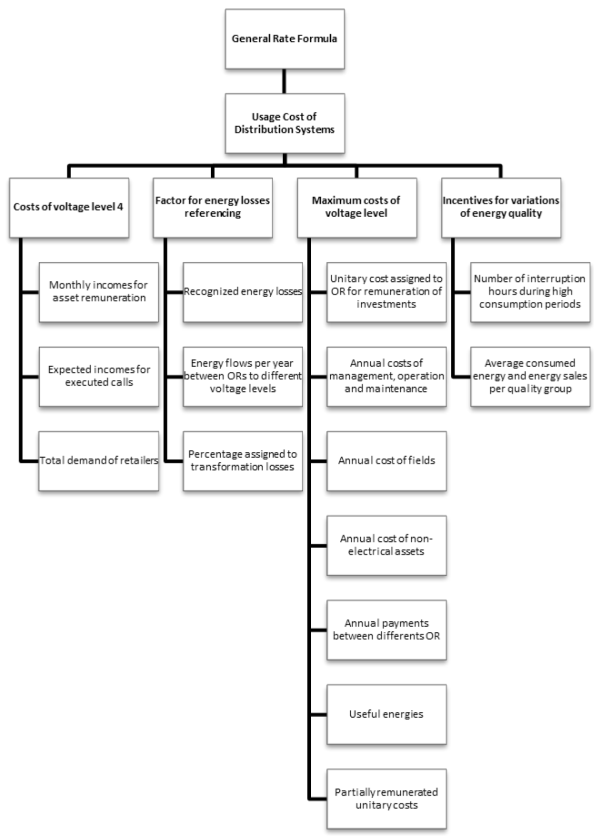

Figure 1. *Parameters that affect the calculation of Usage Costs of Distribution Systems for voltage levels 2, 3 and 4.*

2.2.1. Costs of voltage level 4. $CD_{4,R,m}$

From Eq. (2), costs for voltage level 4 is calculated based on monthly incomes of OR, the expected input from every executed project and total demand of retailers, as shown in Eq. (3):

$$CD_{4,R,m} = \frac{\Sigma_{j=1}^{TR} IM_{j,R,m} + \Sigma_{c=1}^{NCR} IE_{c,R,m}}{\Sigma_{j=1}^{TR} DTC_{j,R,m-1}} \quad (3)$$

where:

c Call

NCR Total number of executed calls in the STR

TR Total number of ORs that belong to STR R

$CD_{4,R,m}$ Costs of voltage level 4 of STR R

$IM_{j,R,m}$ Monthly income of month m, as a remuneration for the use of assets from voltage level 4 of OR j that belongs to STR R

$IE_{c,R,m}$ Expected income of every project c executed in STR R

$DTC_{j,R,m-1}$ Total demand of retailers that attend to users connected to the OR j, belonging to STR R for month m.

It is seen from Eq. (3) that DRP implementation would have an influence on the calculation of costs of voltage level 4. This is a consequence of demand reduction, which could reduce the monthly income received by retailers as a remuneration for the use of assets of voltage level 4 ($IM_{j,R,m}$) (A1); on the other hand, the expected income of each call ($IE_{c,R,m}$) could be reduced if capability of equipment to be installed is also diminished during expansion processes (A1). Finally, total demand of retailers ($DTC_{j,R,m-1}$) could be also reduced for implementation of DRP that incentive the consumption reduction.

2.2.2. Factor for energy measures referencing. $PR_{j,n}$

Factors for energy measures referencing of each voltage level of Colombian National Transmission System (STN in Spanish) considering energy losses of STR and SDL. For voltage level 4, this factor is equal to the recognized losses for CREG, and its calculation is based in technical analysis of each OR and it shows the losses of STR or SDL (A3) (CREG, 2008a; CREG, 2008b).

On the other hand, the factor for referring energy measures to STN for voltage levels 3 and 2 is calculated based on recognized losses for the corresponding voltage level and OR, the energy flows per year between different voltage levels and transformation losses. For voltage level 3 (CREG, 2008b):

$$PR_{3,j} = 1 - (1 - P_{j,3})\left[(1 - P_{j,4})\left(\frac{Fe_{j,4-3}}{Fe_{j,3}}\right) + (1 - P_{j,STN-3})\left(\frac{Fe_{j,STN-3}}{Fe_{j,3}}\right)\right] \quad (4)$$

Where:

$$Fe_{j,3} = max\left[1, (Fe_{j,4-3} + Fe_{j,STN-3})\right] \quad (5)$$

$PR_{3,j}$ Factor for referring energy measures from voltage level 3 of OR j to STN

$P_{j,n}$ Losses to be recognized at voltage level n of OR j. In this case, n corresponds to 3 or 4

$Fe_{j,4-3}$ Energy flow per year between voltage level n and voltage level 3 of OR j. In this case, n corresponds to STN or 4

$P_{j,STN-3}$ Transformation losses for referencing energy losses from voltage level 3 to STN, equal to 0.23%

For voltage level 2:

$$PR_{2,j} = 1 - (1 - P_{j,2})\left[(1 - P_{j,4})(1 - P_{j,3})\left(\frac{Fe_{j,3-2}}{Fe_{j,2}}\right) + (1 - P_{j,4})(1 - P_{j,4-2})\left(\frac{Fe_{j,4-2}}{Fe_{j,2}}\right) + (1 - P_{j,STN-2})\left(\frac{Fe_{j,STN-2}}{Fe_{j,2}}\right)\right] \quad (6)$$

Where

$$Fe_{j,2} = Fe_{j,STN-2} + Fe_{j,4-2} + Fe_{j,3-2} \quad (7)$$

$PR_{2,j}$ Factor for referring energy measures from voltage level 2 of OR *j* to STN

$P_{j,n}$ Losses to be recognized at voltage level *n* of OR *j*. In this case, n corresponds to 2, 3 or 4

$Fe_{j,n-2}$ Energy flow per year between voltage level *n* and voltage level 2 of OR *j*. In this case, *n* corresponds to 3 or 4

$P_{j,n-2}$ Transformation losses for referring energy losses from voltage level *n* of the same OR, equal to 0.23%

It could be inferred from Eq. (4) and Eq. (6) that a reduction in the consumption at certain hour of the day after application of DR programs could lead to a long-term variation in the calculation of losses factors for referring energy measures from voltage levels 2 and 3 to STN. This is due to a reduction in the consumption could diminish energy flows per year between OR to different voltage levels (A4), and in a long-term perspective, technical losses recognized by the CREG (A3). On the other hand, a variation in the consumption habits could require a revision of the percentage assigned to transformation losses, due to this value could change with DR programs.

2.2.3. Maximum costs of voltage level. $CD_{j,n,m}$

The maximum cost of voltage level is equal to zero for voltage level 4, as opposed to costs of voltage levels 2 and 3, which depend on a monthly update calculated considering the maximum approved cost for the respective voltage level and National Consumer Price Indices. This relationship is shown in (8):

$$CD_{j,n,m} = CD_{j,n} * \frac{IPP_{m-1}}{IPP_0} \quad (8)$$

Where:

$CD_{j,n,m}$ Maximum cost of voltage level *n* of OR *j*, corresponding to month *m*

$CD_{j,n}$ Maximum approved cost of voltage level *n* of OR *j*

IPP_{m-1} Total National Consumer Price Index corresponding to month *m*-1

IPP_0 Total National Consumer Price Index corresponding to December 2007.

Total National Consumer Price Index is reported by Colombian National Administrative Department for Statistics (DANE in Spanish) and it can be assumed as a constant for variations in electricity demand. This implies that the maximum cost of the respective voltage level will only depend of the maximum costs approved for that voltage level, which are calculated using (9) (CREG, 2008a; CREG, 2008c):

$$CD_{j,n} = CDI_{j,n} + \frac{AOM_{j,n,k} + CAT_{j,n} + CAANE_{j,n} + O_{j,n}}{Eu_{j,n}} + CD_{j,3-2} \quad (9)$$

Where:

$CD_{j,n}$ Maximum cost for OR *j* of voltage level *n*, referred to 2007 December Colombian pesos (COP)

$CDI_{j,n}$ Unitary cost assigned to OR *j* as a remuneration to investments of voltage level n assets

$AOM_{j,n,k}$ Annual cost of management, operation and maintenance assignable to OR *j* for voltage level *n*

$CAT_{j,n}$ Annual cost of lands for OR *j* of voltage level *n*

$O_{j,n}$ Equivalent annual cost of non-electric assets for OR *j* for voltage level *n*

$CAANE_{j,n}$ Annual payments of OR *j* to other OR for the use of SDL, related to connections at voltage level *n*

$EU_{j,n}$ Useful energy of OR *j* at voltage level *n*

$CD_{j,3-2}$ Unitary cost of voltage level 3 that is partially remunerated at voltage level 2 for OR *j*. This cost is equal to zero when maximum unitary cost is calculated for voltage level 3.

Due to DR affects the maximum costs for each voltage level only for parameters shown in (9), the following relation between affected parameters and aspects is obtained:

Unitary cost assigned to OR for remuneration of investments, which at the same time depends on the input energy to the power system and the power losses at the network of each OR (A1, A3, A4)

Annual costs of management, operation and maintenance, which also depend on investments of OR (A1)

Annual cost of lands, which also depends on constructive units and recognized areas for these units. (A1)

Equivalent annual cost of non-electrical assets. This cost also depends on existing and new assets. (A1)

Annual payments of an OR for usage of SDL. This payment depends on the imported energy and the maximum estimated cost for the exporter (A1, A3, A4)

Useful energy, which also depend on the input energy and the network losses of each OR (A3, A4)

Finally, the unitary cost that is partially remunerated for voltage level 2 is defined as a fixed quantity for each OR. DR might require a long-term revision of a novel methodology for calculation of this cost.

2.2.4. Incentives for energy quality variations. $\Delta Dt_{j,n,m}$

The last parameter that affects the Usage Cost of a Distribution System for voltage levels 2 and 3 (considering that this cost is equal to zero for voltage level 4) is the incentive for a three-month variation of energy quality. This parameter cannot exceed a 10% of Usage Cost (positive or negative) and it is calculated considering energy discontinuity indices and electricity rationing costs (CREG, 2008a; CREG, 2010a), as shown in Eq. (10).

$$\Delta Dt_{n,m} = \left(IRAD_{n,p_{m-4}} - ITAD_{n,p_{m-4}}\right) CRO_{m-1} \qquad (10)$$

Where (CREG, 2008a):

$$IRAD_{n,p_{m-4}} = \frac{1}{2}\left[\sum_{k=k_1}^{k_2}\left(\frac{1}{G}\sum_{q=1}^{G}\frac{\sum_{t=1}^{N_{n,q,p,k}} DRT_{n,t,q,p,k} * EPU_{n,q,p,k} * NU_{n,t,q,p,k}}{VT_{n,q,p,k}}\right)\right] \qquad (11)$$

$$ITAD_{n,p_{m-4}} = \frac{1}{G}\sum_{q=1}^{G}\frac{\sum_{t=1}^{N_{n,q}} DTT_{n,t,q,p} * EPU_{n,q,p} * NU_{n,t,q,p}}{VT_{n,q,p}} \qquad (12)$$

p Three-month period of each year for the calculation

k Reference years, where k_1=2006 y k_2=2007

q Quality group

G Number of quality groups where the OR attend end-users

$IRAD_{n,p_{m-4}}$ Grouped reference index for discontinuities of three-month period p where month *m*-4 belongs

$ITAD_{n,p_{m-4}}$ Grouped three-month index for discontinuities, estimated according to energy quality information of the three-month period *p* where month *m*-4 belongs

CRO_{m-1} Electricity rationing cost *CRO1* calculated by Colombian National Unit for Mining and Energetic Planning (UPME in Spanish) for month *m*-1

$N_{n,q,p,k}$ Total number of transformers of an OR that are connected to voltage level *n* and quality group *q*, during the three-month period *p* of year *k*

$DRT_{n,t,q,p,k}$ Reference duration calculated as a sum of hours of energy interruptions of transformer *t*, connected to voltage level *n* of quality group *q*, during the three-month period *p* of year *k*

$EPU_{n,q,p,k}$ Average consumed energy in kWh/h for end-users of quality group q of voltage level n, during the three-month period p of year k, according to the information reported by the OR in the commercial database of Colombian Information System (SUI in Spanish).

$NU_{n,t,q,p,k}$ Average number of users of transformer t, connected to voltage level n, of quality group q, during the three-month period p of year k

$VT_{n,q,p,k}$ Energy sales associated to quality group q of voltage level n during the three-month period p of year k in kWh, according to the information reported by the OR in the commercial database of SUI.

$DTT_{n,t,q,p,}$ Three-month duration calculated as a sum of hours of energy interruptions of transformer t connected to voltage level n of quality group q during year k

Electricity rationing cost is issued by UPME and can be considered as a constant value. Therefore, incentives for a three-month variation of energy quality will only depend of reference indices. $IRAD_{n,pm-4}$ index relates average non-supplied energy to each unit of supplied energy of an OR during a period of time used as a reference, instead of $ITAD_{n,pm-4}$, which relates the same quantity during a three-month evaluation period.

DR might reduce the number of interruption hours caused by transformer overloads during high consumption periods, i.e., values of parameters $DRT_{n,t,q,p,k}$ and $DTT_{n,t,q,p,k}$ could be reduced (A5). Additionally, DR might reduce the average consumed energy during the three-month evaluation period and energy sales per quality group, due to these depend at the same time on average checked energy (A2) (CREG, 2008a; CREG, 2009; CREG, 2010b).

2.3. Usage Cost of Distribution Systems for voltage level 1

Due to calculation of Usage Cost of Distribution Systems for voltage level 1 include additional parameters, which are not easy to include in a sole expression as for voltage levels 2, 3 and 4, this section includes its description. In this case, Usage Cost is given by (13):

$$Dt_{j,1,m} = \frac{CD_{4,R,m}}{1 - PR_{1,j}} + \frac{CD_{j,2,m}}{1 - PR_{(1-2),j}} + CDI_{j,1,m} + CDM_{j,1,m} + \Delta Dt_{j,n,m} \quad (13)$$

Where

$Dt_{j,1,m}$ Usage Cost for voltage level 1 of OR j for month m

$PR_{1,j}$ Factor for referring energy measures of voltage level 1 to STN in the system of OR j

$CD_{j,2,m}$ Maximum cost for voltage level 2 corresponding to month m of OR j

$PR_{(1-2),j}$ Factor for referring energy measures from voltage level 1 to voltage level 2, in the OR j

$CDI_{j,1,m}$ Maximum cost for voltage level 1, for investments during month m of OR j

$CDM_{j,1,m}$ Maximum cost for voltage level 1, for management, operation and maintenance concepts in networks of voltage level 1 during month m of OR j

It can be verified that DR affects all maximum costs of voltage levels 2 and 4, the factor for referring energy measures from voltage level 1 to STN and the quality incentive for voltage level 1, similar to effects on voltage levels 2 and 3. However, two additional maximum costs are added to Eq. (13), a first one related to investments and a second one related to management, operation and maintenance costs for networks of voltage level 1. Costs of existing assets and investment costs are considered for the calculation of the former (A1) and variations for energy sales at voltage level 1 (A2)-(A3); management, operation and maintenance costs per year are considered for the calculation of the latter (A1).

3. Results and discussion

Nowadays, worldwide DRP offered are classified in two groups: Incentive-Based Programs (IBP) and Price-Based Program (PBP). IBPs offer discounts, payments or penalties to participants as a function of its own participation in the program, instead of PBP, which participants receive periodical price signal (Marulanda, 2014). Both programs pursue a reduction or load relocation, therefore the impact on rates is reflected on the same parameters mentioned earlier, regardless of implementation of IBPs or PBPs.

Assuming that current structure of Usage Cost of Distribution Systems is preserved, two parameters are identified and suggested for a short-term revision by CREG, OR and retailers. The first of these parameters is Usage Cost for voltage level 4 ($CD_{4,R,m}$), which is related to monthly total demand of retailers that operate a STR. As shown in Eq. (3), monthly reductions of energy consumers that participate in a DRP may produce increases in Usage Costs of all end-users of the respective STR and for all voltage levels. The second of these parameters is the incentive for variations in energy quality ($\Delta Dt_{j,n,m}$), which is related to service interruption times and energy consumed by end-users during a three-month period. Under this scenario, reductions and load relocations of end-users may lead to an increase in service quality of OR, which generate incentives for OR but increments on Usage Costs of Distribution System for end-users.

Impact of DR on the remaining parameters of Usage Costs depends on dynamics that are created between OR and modifications on consumption habits. These variations cannot be supported based on a qualitative analysis only, and are out of the scope of this research. However, it is important to highlight that some benefits are obtained from energy flows between ORs ($Fe_{j,n-2}$) and useful energies ($Eu_{j,n}$); these benefits motivate the coordination of demand resources of ORs and retailers, although increments on end-users rates may appear.

On the other hand, there are several DRP contained in IBPs and PBPs that allow a Direct Load Control (DLC) from ORs. Programs that allow DLC give a greater certainty to retailers and ORs related to real reduction on consumption when required (according to commitments of the DRP). Therefore, programs based on DLC would allow planning of reliable DR programs. In fact, CREG, retailers and ORs could analyze remuneration for DRP with DLC, based on economic benefits that might be obtained from current general rate scheme and load disconnection capability. In contrast, programs that are not DLC-based, have a greater uncertainty level for OR and retailers; due to load reduction is left as an end-user decision. In this case, a detailed characterization of demand by retailer and voltage level is required, for aiming to future regulating strategies.

Table 1. *Summary of obtained results.*

Parameter	Aspects	Voltage level
Cost of voltage level 4 $CD_{4,R,m}$	A1 and A2	1, 2, 3 and 4
Factor for energy measures referencing $PR_{n,j}$	A3 and A4	1, 2 and 3
Factor for energy measures referencing $PR_{4,j}$	A3	4
Maximum costs of voltage level $CD_{j,n,m}$	A1, A3 and A4	1, 2 and 3
Incentives for energy quality variation $\Delta Dt_{j,n,m}$	A2 and A5	1, 2 and 3
Maximum cost for investments, for voltage level 1 $CDI_{j,1,m}$	A1	1
Maximum cost for voltage level 1, for management, operation and maintenance $CDM_{j,1,m}$	A1, A2 and A3	1

Finally, obtained results in previous sections are summarized in Table 1. First column of Table 1 indicates parameters of Usage Costs in Distribution Systems that may vary after an implementation of DRP in Colombia. Second column of Table 1 presents how this parameter is affected considering the aspects explained in section 2. Similarly, third column of Table 1 indicates voltage levels that are affected in rates, after a variation of the parameter indicated in the first column. Under current regulation, the main potential of DR could be reached through programs that affect a greater number of end-users, i.e., users that are reflected in a greater voltage level; in this case, a DRP that impacts a voltage level 4 cost ($CD_{4,R,m}$) will be reflected in all voltage levels. Additionally, aspects A1 and A3 have a greater influence in several factors, therefore, variations in operating conditions of a network should be considered during the construction of a regulation that features DR.

4. Conclusions

In this research, several parameters of current Usage Cost calculation that might be affected after the implementation of DRP in Colombia were identified. The results of this research allow a classification of DR impact according to five aspects: equipment capacity (A1), energy sales (A2), energy losses (A3), payments between network operators (A4) and energy service quality (A5). This classification gives a general idea of the impact of DR in Colombia for distribution systems in a rate scope, showing that Usage Cost for voltage level 4 has a considerable impact for a greater number of end-users, instead of aspects A1 and A3, which affect a greater number of rate parameters. The developed analysis shows that two parameters require a short-term revision by CREG, ORs and retailers: Usage Costs for voltage level 4 and incentive for variations in energy service quality. Finally, characteristics of DRP and their relation to future regulations are discussed, revealing the importance of considering variations in network operating conditions for the construction of future regulations. Quantitative analysis of DR impacts on each component of the General Rate Formula is proposed for future researches.

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