Management of Voltage Control Using Distributed Generation in the Colombian Power System: a system dynamics approach

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Abstract— *This paper presents a study on the penetration of Distributed Generation (DG) under the consideration of a proposal for trading, environmental, and technical incentives, in the Colombian power system. To quantify the technical incentives, we simulated a part of the Colombian grid that presents some busbars with low levels of voltage. We connect DG to the busbars "problem" and we found an increase in voltage that in a controlled manner can to help to better quality and continuity of electricity supply. Environmental and trade incentives were quantified using international experiences. In addition, we built a system dynamics model to evaluation the complete proposal. We found that the current incentives presented in the Colombian regulation such as tax breaks are insufficient to cover the total costs. Moreover, environmental incentives can be an efficient way to promote renewable energy use in Colombia, in order to achieve, more generating capacity with less pollution indices; and technical incentives in conjunction with environmental incentives can improve further the growth of DG in Colombia. Thus, the DG diffusion becomes an additional tool for the operator of the interconnected system to make voltage control, improve the quality, and security of electrical power systems.*

Keywords— Ancillary Services, Distributed Generation, Reactive Power, Voltage Control, System Dynamics.

INTRODUCTION

Nowadays, ensuring a secure electricity supply is an important policy objective in virtually all modern economies (IEA, 2002). This objective deals not only with availability of electricity but also with power quality. The power system operator must maintain the frequency and the stable voltage profiles within the required ranges (Bacon and Besant, 2001). The system operator counts with technical support services known as ancillary services in order to satisfy the requirements. Voltage control, frequency control, and black start services are the most frequently used ancillary services (Bacon and Besant, 2001).

Voltage control is related to reactive power (Q) supply in the systems busbars using different equipment and technologies (Kirby and Hirst, 1997). This control is known as local control, since the reactive power can be supplied by the demand and thus reduces the voltage drop at busbars and improve the indices of power quality (Kirby and Hirst, 1997).

Distributed Generation (DG) has the potential to provide voltage control and a number of collateral advantages (Viawan and Karlsson, 2008). DG also helps decongesting transmission grids (Viawan and Karlsson, 2008) because it is located near consumption centers. It also helps generating or absorbing the reactive power required by the system in order for the voltage in the nearby busbars to meet regulations (Gomez, 2002). Regarding environmental issues, DG uses electrical plants with capacities below 20 MW and has the capacity to use renewable resources thus helping to reduce harmful emissions to the environment (Diaz, 2007).

This paper presents a system dynamics diffusion model (Sterman, 2000) to study DG integration in the Colombian power system.The simulation model allows the analysis of DG growth when trade, environmental and technical incentives are included as an addition to the tax exemption incentives currently provided by the regulations in Colombia.

The study was conducted in a Colombian sub-region known as the Coffee Region, which includes Caldas, Quindio and Risaralda (CQR). This is part of the Southwest operative area of the Colombian power system. We have selected this region for three reasons: *i.* there are voltage stability problems due to the connection of highly inductive loads (XM, 2009); *ii.* DG seems to be a feasible solution to improve electricity quality; and *iii.* There is a potential for DG due to the existence of water resources and the raw material for biofuel production (Diaz, 2007).

The paper is organized as follows. Section 2 explains the technical aspects of voltage control when using DG, Section 3 examines the economic analysis for the model, Section 4 shows the implementation of the DG diffusion model in a subregion of the southwest operational area, Section 5 evaluates alternatives to the studied incentives to implement DG diffusion, and Section 6 concludes.

TECHNICAL ASPECTS OF DG VOLTAGE CONTROL

This section explains the behavior of loads of high inductive value and its effect on the waveform and on voltage quality. It also shows the results of the impact of DG on Voltage control and Q supply to the electrical grid, in an area of the Colombian power system corresponding to a subregion of the southwest area.

Voltage control is an ancillary service that helps to keep voltage on a node or busbar within the values required by the regulator (Assili et al., 2008). Nodes of stable voltage profiles have small losses because of the active and reactive power occurring in the lines interconnecting such busbars (Kundur, 1994).

Voltage control is important because disturbances in the voltage sinusoidal waveform might damage the equipment and in turn the industrial loads, as consequence the other users will operate inadequately (Kundur, 1994). Thus, the voltage control improves the quality of the local supply and the nearby busbars. DG has been recognized as a solution to improve voltage control (Hirst, 2000). DG keeps the voltage within the range required by system, through of the production and availability of Q injection to solve the problems of low-voltages busbars, and with the capability to absorb Q for high-voltage busbars (Kirby and Hirst, 1997).

Behavior of industrial loads in the power system

Industrial loads have high inductive value, which means, loads of nonlinear behavior that need to consume high amounts of reactive power of the electrical grid (CREG, 1995). The reactive power sharply declines and changes the sinusoidal waveforms of the voltage busbars and of the busbars near the operational area. According to the regulator, voltage waveform should be evaluated by an index called PST (Percibility Short Time) (Ramírez and Cano, 2006), which defines that an electrical power system meets power quality when registering a PST between 0.9 and 1.

Figure 1 shows the record of a device measuring the PST index in a busbar of the operational area CQR for a 24 hour period. The chosen busbar is connected to an iron and steel industry. Unstable behavior is observed in its daily operation, and it gets worse between 13:00 and 15:00 hours as the furnaces to melt metal and to develop chemical compounds begin operating. This increase in consumption in high inductive loads causes a PST index of 0.2, which means a system with a distorted voltage wave that affects not only their own consumption but also the consumption of the nearby loads.

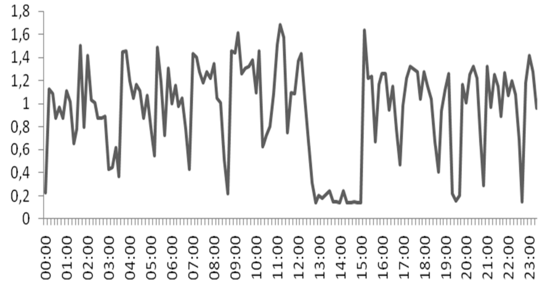

Figure 1. *PST index*

The operator of the Colombian power system uses centralized generators to manage Q supply and Voltage control. However, these generators suffer a decrease of nominal active power at the time of delivery changes or when absorbing reactive power due to operation restrictions (Kundur, 1994). This condition reduces the net generation capacity and it might affect the power system security indices (Assili et al., 2008).

Impact of DG in voltage control in electric power systems

As we previously mentioned, voltage waveform disturbances cause low quality electric supply. These disturbances, widespread in the interconnected power system, might trigger voltage collapse and in severe cases can lead to operational decomposition and total or partial blackout. The operational area in which the study was carried shows a number of voltage events out of range, which justifies the implementation of solutions to avoid possible voltage collapse. The results of the technical study based on DG connection in the busbars where voltage was out of the regulated range are shown below.

Case study

The region CQR includes 22 busbars, two busbars connected to 220 kV, six busbars of 115 kV and 14 busbars connected to 33 kV. The loads connected to the electrical grid had a high inductive value because of the industrial activity.

This system has voltage problems in busbars 19 and 22 which are connected to 33kV. There are five cases in the study that take into account the connection of distributed generators of 10 MW in the busbars where voltage is out of the permitted range. . Table 1 shows the characteristics of each case.

Table 1. *Cases of the technical study using DG for Voltage control*

Cases	**Description**
1	System without DG
2	DG only in busbar 22
3	DG busbar 22 and Capacitor Banks
4	DG in busbar 19
5	DG in busbar 22, 19 and Capacitor Banks
6	Only Capacitor Banks

Figure 2 shows voltage behavior in busbars 19 and 22. Regulation determines that the minimum voltage in a 33kV busbar is 0.9 p.u. (CREG, 1995). In this system, busbar 19 had a voltage of 0.6pu. The voltage increases to 0.97 when it is connected to DG thus complying with regulations. When Capacitor Banks (CB) is connected, the result is 0.98 improving the magnitude but with no substantial change. In case five, voltage increases up to 0.7p.u., which shows the need to implement DG due to the fact that even though CB has the same magnitude as the distributed generator, does not increase voltage in busbar 19 in the same proportion.

In the case of busbar 22 (fig. 2), voltages is improved when DG is installed. It is important to state that for voltage control in this busbar it is possible to use the BC, since it shows a favorable behavior in the busbar voltage magnitude.

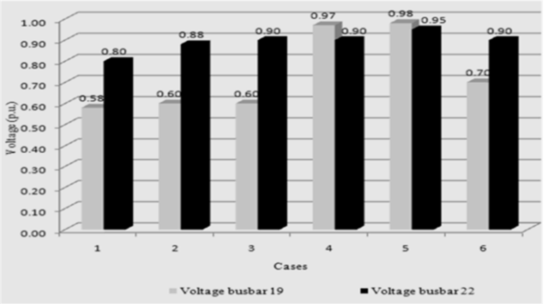

Figure 2. *Voltage in busbars 19 and 22*

Figure 3 shows how the magnitudes of electrical losses are reduced more than 80% when DG is installed on nodes with low voltage problems. Losses decrease proportionally to the increase of voltage in the busbars with problems. (Case three and four). Thus, DG provides local control with regional implications. The most visible consequences are voltage increase, decongestion in lines, and loss reduction.

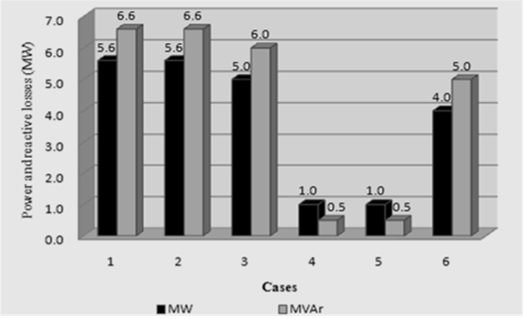

Figure 3. *Losses of Active and Reactive power in the lines between busbars 17 and 19*

It is important to note that implement DG in electrical grid needs a technical previous study, because DG can cause worse damage to power quality in busbars that generate surges.

It is possible to evaluate the effect of DG in the voltage magnitude regarding the number of MW installed using the results of the simulations. Figure 4 shows the above mentioned behavior of the voltage in per unit when we increase the relationship between DG_potential and IDG.

Installed Distributed Generation (IDG) factor (in x axis) is the factor that allows the evaluation of the capacity of the DG installed with relation to the DG projected; in other words, the factor determining the impact of DG installation in the magnitude of the voltage in the busbars when the DG system is installed.

The IDG factor shows in figure 4, is simulated in an electrical model. The voltage indices (in y axis) fail to improve in all the system busbars when the relation of the IDG regarding DG_potential is lower. At At the same way, the power quality decreases when the relation is very high, impairing the value of the voltage magnitude and its connected loads. This factor is use in DS model to limit the growth in technical incentives as will be explained later in section 4.2.

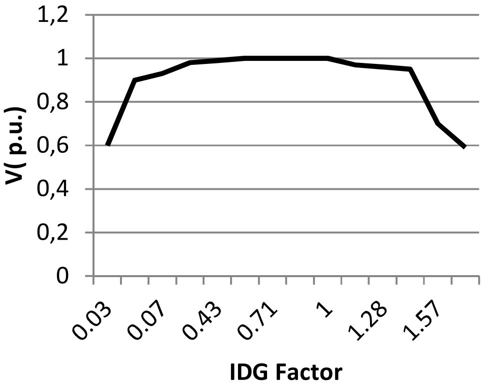

Figure 4. *IDG factor for the simulation model*

ECONOMIC ANALYSIS OF DG DIFFUSION

Before modeling DG diffusion, we consider an economic analysis, which provides information about the operation and investment costs when implementing DG. Of particular interest, the analysis is made for DG with organic materials to produce biofuels. Thus, we make the feasibility analysis of biofuel plants. These plants are expected to be beneficial in terms of pollution indices (IEA, 2007). Furthermore, Colombia has begun to develop successful projects for biofuel production due to its agricultural potential. Some examples are the sugar mills and the African palm cultivation.

Operation costs are based on costs of generation associated with fuel prices, administration and maintenance (IEA, 2007).Investment costs are related to the plant capital costs. According the International Energy Agency (IEA), capital costs for these types of technologies will decrease in time because an improvement in the efficiency and consumption of these technologies is expected (IEA, 2007).

In (IEA, 2007) the levels of investment and the average generation costs for different technologies are compared. It also shows a projection that in 20 years alternative energy generation will reduce investment and generation costs because its use will be increased worldwide.

The current capital costs of DG projects using biomass are elevated with regard to the incurred costs by centralized conventional generation projects (Huacuz, 2010). For this reason it is essential to count on economic incentives to increase this type of generation.

We found that the experiences in countries such as Spain, United States, and Germany show that incentives are crucial (Iberdrola, 2010); especially in the initial construction and operation period. In the medium term, incentives are important to increase the number of distributed plants with the thought of using them as a complement for the operation of the interconnected systems, thus creating an additional tool for voltage control.

Economic incentives for DG can be justified because they can be used to improve power quality through the provision of ancillary services (Viawan and Karlsson, 2008). In addition, DG helps to postpone additional labor in transmission and distribution systems because surges in the system loads are reduced which allows the usage of conductors of the same caliber (Kundur, 1994), and transformers, protectors and generators of the same capacities (Hirst, 2000).

DG has also the potential to use a broad portfolio of renewable and nonrenewable technologies (Rodriguez, 2009). The benefits are not only for the environment (Hammons and Boyer, 2000), but also to provide greater flexibility and reserve margin to increase reliability (Kundur, 1994) during periods of drought and also in times of fossil fuel supply and price volatility (Rothwell and Gómez, 2003).

Although the regulatory framework does not include DG as a generation option, industries such as oil, cement, sugar mills and others have machinery to carry out self-generation and co-generation processes (alcongen, 2009).

The main barrier for the diffusion of DG in Colombia are costs and is that incentives are available only in the investment period and are indirect because they are based on the tax exemption given to plants under construction (Rodriguez, 2009).

In this sense, we propose to test the effect of environmental incentives for operation as well as technical incentives related to voltage and reactive control as a diffusion mechanism of DG in Colombia.

MODEL TO PROMOTE THE USAGE OF DG IN COLOMBIA

The electric industry deregulation introduced decentralization and competition (Hunt and Shuttleworth, 1996). The decentralization increases the complexity in the system operation because before, in a regulated system, the utilities were vertically integrated and cooperated voluntary to operate a reliable system by coordinating their resources with neighboring utilities (Chao and Huntington, 1998), knowing that regulated tariffs would cover bundled costs (Hirst and Kirby, 1998). Under deregulation, the system operator is responsible for system reliability (Gómez, 2002). It buys different ancillary services from generators and users to maintain a reliable system (Hirst, 2000). However, legal responsibilities of system operators must be clearly defined by new regulations (Rothwell and Gómez, 2003).

On the other hand, a major objective of electricity deregulation is to achieve a workably competitive wholesale market (Rothwell and Gómez, 2003). Wholesale electricity markets have high price volatility due to daily and seasonal variations in supply and demand (Hunt and Shuttleworth, 1996). This raises two important issues under deregulation: demand responsiveness to price variations and new investment in generation resources (Hunt and Shuttleworth, 1996).

Larsen and Dyner, 2001 showed that the uncertainty and the risks increase when you want long-term studies, making it difficult to create highly accurate predictive models in deregulated electrical systems.

An alternative is to make models to understanding the dynamic path into the future and between the tools useful for strategy formulation in utilities which needs to be added after a deregulation is the business dynamics or the System Dynamics (SD) (Sterman, 2000).

The DS has been used in the deregulated electricity sector for the analysis of investment in generation process (Bunn and Larsen 1992), (Ford, 1999) and (Arango, 2007). It has also been used in studies on competition between generation plants that use different primary energies (Quadrat-Ullah and Davidsen, 2001), (Botterud et al., 2002) and studies on the inclusion of alternative energy in decentralized markets (Ford et al., 2007), (Zuluaga and Dyner, 2007).

The model is inspired by the Bass classical diffusion model (Bass, 1969). This model is adapted to the features of the system, in particular the use of DG integration as a function of the different incentives in place and proposed for this technology. We first present the dynamic hypothesis for the model; thereafter, we present the formal model.

Dynamic hypothesis

The feedback loop diagram reported in Figure 5 represents the dynamic hypothesis for the DG diffusion. It shows the main variables and its relations to analyze DG diffusion in the Colombian power system taking into account additional incentives. Note that this approach is thought for a particular region, instead of the whole system.

The main driver for the DG in the investment, such that the increase in invest increase the installed capacity of DG, after a delay. The Colombian power system has a market oriented structure, which means that investments are driven by the profitability of the investments.

The profitability is increased by endogenous incentives, such as technical and environmental incentives; as well as exogenous incentives, which are the regulatory incentives. The environmental incentive is justified with the fact that there is a CO_2 and NOx reduction (Denne and Waikato, 2006) since this generation has lower environmental impact when compared to large central power systems (IEA, 2007).

The second incentive is aimed to the use of DG as a tool to provide support services to the power system, specifically to pay distributed generators to help maintain voltage and reactive levels within the required ranges in order to improve quality and safety indices.

The technical incentive has a limit due to operational constraints of the systems of transmission. In particular, an inordinate amount of DG can cause electrical imbalances at any point within an interconnected transmission network can have immediate and severe repercussions for the quality and deliverability of electricity throughout the whole interconnected grid (Kundur, 1994).

The model also takes into account existing regulatory incentives. Currently in Colombia there is tax breaks for sales from alternatives energies (wind and biomass resources) for 15 years. For this exemption, generators are required to hold carbon emissions certificates and to invest fifty percent of certificates in social infrastructure projects (Law 788, 2002). Once in full operation, the generator agents do not receive any type of remuneration or additional bonuses for the use of renewable or low environmental impact resources.

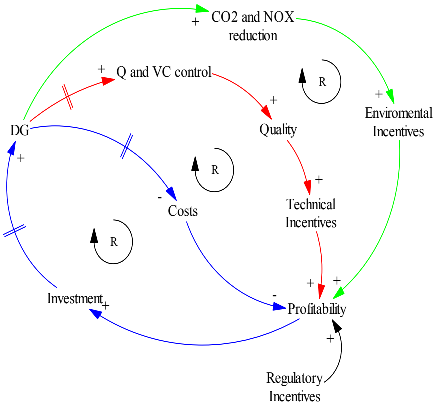

Figure 5. The feedback loop diagram - DG diffusion

Formulation of the simulation model

The feedback diagram in Figure 5 is translated into a formal visual diagram at a more detailed (operational) level, which distinguishes between stock variables (i.e. state variables) and flow variables (or rates) (Sterman, 2000).

This type of mapping is shown in Figure 6. The visualization used is from one of the specialist simulation software available for this type of simulation; stocks accumulate resource flows and characterize the memory of the system. Stock variables (boxes) can only change when in the associated flows changes. The stock and flow diagram provides the structure of the actual mathematical formulation underlying the model.

We can observe from the macrostructure of the model sketched in Figure 5, the main stock or state variables of the model are Distributed Generation Potential *(DG_Potential)* and Installed Distributed Generation *(IDG)*. The level of each state variable is defined in terms of the associated flows.

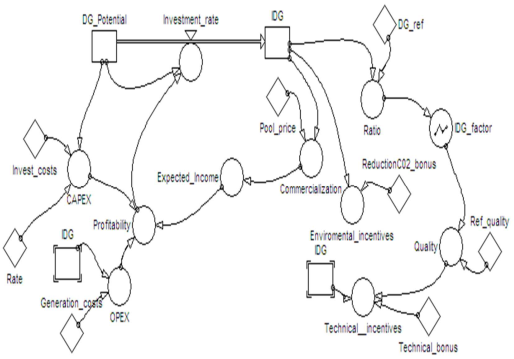

Figure 6. The formal diagram - DG diffusion

The model formulation takes into account the Bass diffusion model (Bass, 1969). This model solved the startup problem by assuming that potential adopters become aware of the innovation through external information sources whose magnitude and persuasiveness are roughly constant over time. Bass assumed the probability that a potential adopter will adopt as the result of exposure to a given amount of advertising and the volume of advertising and other external influences each period are constant (Sterman, 2000).
In our model, potential adopters and adopters are represented in levels *DG_potential and Installed DG.* The growth of DG will depend on *investment_rate*, which is affected by the perception of potential generating agents about invest in DG and the profitability given by incentives. The equations associated with the above described process are:

$$\frac{\partial DG\_potential}{\partial t} = -Investment\_rate \qquad (1)$$

$$\frac{\partial IDG}{\partial t} = Investment \qquad (2)$$

$$Investment\_rate = DG\_potential * profitability \, (3)$$

Profitability can be considered how the difference between the expected income or purchase price with incentives, and the capital and operational costs. Capital costs are called Capital Expenditure (CAPEX) and operational costs are called Operating expenditure (OPEX). CAPEX is the *investment cost* in plant property and equipment and OPEX is an ongoing cost for running a product as it is a cost associated with the size of productivity. Equations associated with this process are:

$$\Pr oftability = \left(Expected\_Income - CAPEX - OPEX \right) \quad (4)$$

$$CAPEX = \frac{Investment\_\cos t * DG\_potential}{1 + Rate} \qquad (5)$$

$$OPEX = Generation\_\cos t * IDG \qquad (6)$$

Expected Income change for each scenario evaluated since they depend on the number of MWh of DG sold in the Colombian market and incentives approved by the regulator.
The commercialization of P in DG is based on the commercialization of plants with installed power lower than 20 MW and it is described in equation (7) using a non-centralized dispatch. The price paid to each generator is the power Pool price (Rodríguez, 2009).

$$Commercialization = IDG * Pool\_price \quad (7)$$

The Pool_ price parameter is taken from the XM record, the organization in charge of electricity market in Colombia, to calculate the fee they are paid for participating in the electricity market (XM, 2009).
The environmental incentives are evaluated by the air quality that measures the amount of greenhouse gases that are emitted into the environment at the time of generation, especially when fossil fuels are used.

Equation (8) defines the remuneration for the CO2 and NOx reduction and is given by the reduction bonus and the installed DG capacity.

$$Environmental\_incentives = IDG * \text{Re}duction\_bonus\_CO_2 \qquad (8)$$

Technical incentives are implemented when DG provides voltage and reactive control services. As demonstrated in the case study, DG allows voltage increase in the connecting and surrounding busbars, situation favorable while not exceeding the regulatory ranges, which depend on the voltage level.
A magnitude of DG reference was found for this case. This magnitude corresponds to the number of MW of installed DG that can be connected to the electrical grid prior to causing quality problems such as fluctuations in nominal values of busbar voltage, voltage collapse, among other quality problems associated with the voltage waveform. *The IDG* factor is determined from the relationship between *DG reference* and the *IDG* (see section 2.2.1).
The quality of the system at a given time might be known using the result of *IDG factor*. It is necessary to adjust this quality to the regulatory voltage values, because value is compared to the *quality_reference.*

$$Quality = IDG\_factor * quality\_reference \qquad (8)$$

Resolution 025 of 1995 determines the permitted ranges according to the voltage level. In this case, voltages of 115 kV were used and the permitted range was between 90-110% of nominal voltage, and even though the quality reference is the nominal value, the regulator allows controlled variations without losing quality. The technical incentives, then, would be granted as long as the voltage is maintained within this range. The following equations mathematically describe this behavior:

$$Technical\_incentives = IF(103.5 < Quality < 126.5,$$

$$IDG * Technical\_bonus, 0) \qquad (9)$$

The parameter of *Technical bonus* corresponds to payment received by a generation plant for providing the ancillary service of secondary regulation of frequency or Automatic Generation Control (AGC). This value was used in the model because the AGC service is the only ancillary service regulated in the Colombian electricity market.

EVALUATION

This section evaluates each of the proposed incentives. We first develop a base scenario to compare with. The base scenario considers the existing indirect incentives and the sale of generated energy at stock market prices. The simulation experiments allow observing the effect on the Colombian electrical power system.

Base Scenario

The base scenario is the worst scenario because only considers the indirect incentives such as income tax and interest rate exemption.

The benefit is annual remuneration for MW sales, the model uses the actual price paid per MW in bilateral contracts because these plants have a capacity lower than 20 MW and according to the Colombian regulation (CREG 024, 1995), these plants are not obligated to participate in the daily auction.

Figure 7 shows the IDG and the DG_potential for the base scenario. It shows that and steep growth in the first half and smooth in the second half, which is a goal seeking behavior where IDG reaches to the need amount of DG over the time horizon.

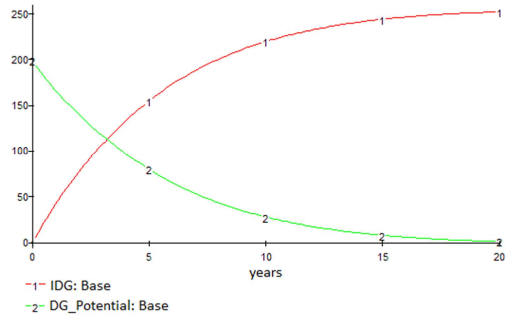

Figure 7. *IDG and DG_potential evolution over time in the base scenario.*

Figure 8 shows the behavior of profitability, which is defined in this model as benefit – cost relation. When this relation is greater than 1 the project is attractive from the financial point of view. Therefore, the base scenario shows that even though profitability increases in 20 years, it does not overcome the unit threshold, thus the Project is not financially justified.

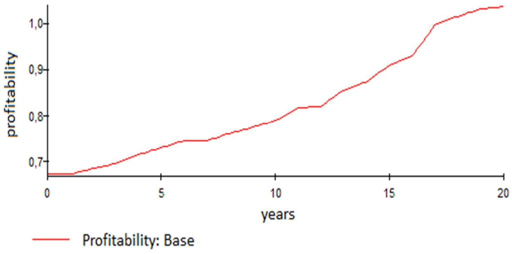

Figure 8. *Profitability over time in the base scenario*

Scenario 1

The first scenario of analysis is characterized by the incorporation the inclusion of environmental incentives. The incentives are given due to the reduction in emission of greenhouse gases such as CO_2 y el NOx.

Environmental incentives were implemented in the model as a direct subsidy which the government defines a payment to be handed out during a period of time to producers of alternative energy.

The bonus system or in tariffs has been successful in Germany, where premiums vary according to type of primary energy used, premiums range from $ 5 per MWh to $ 15 per MWh (Huacuz, 2000). In the Unites State these incentives are 1 cent per kwh (Hammons and Boyer, 2000). In China, rates are set according to the average price of coal in the relevant province, with a premium of about 3 cents per kWh (Denne and Waikato, 2006). Figure 9 shows the development of IDG. The IDG reaches the DG reference value faster with the environmental incentives compared with the base scenario, in only 10 years.

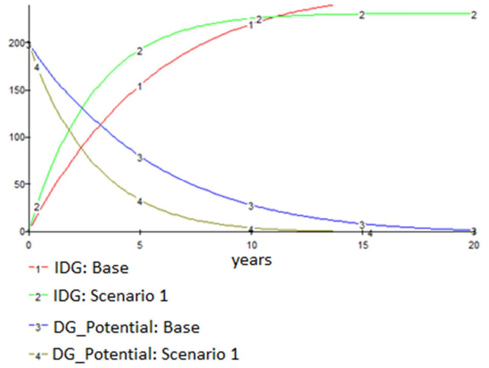

Figure 9. IDG and DG_Potential evolution over time in the base and scenario1.

Figure 10 shows that projects benefit the environment and that receive financial remuneration have income or profits greater than costs, and a profitability value greater than one. The profitability growth over a 20 year period has an increasing behavior, the comparison with the base scenario, indicating that incentives will trigger investors to think of this type of generation.

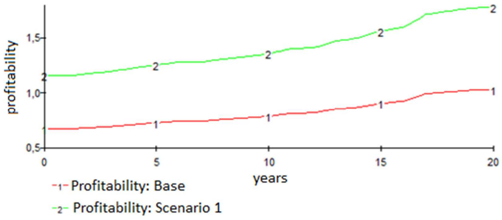

Figure 10. *Profitability over time in the base scenario*

Scenario 2

All the characteristics of Scenario 1 in addition to the modeling of technical incentives are taken into account in the implementation of scenario 2. This scenario has the most favorable behavior since the plants of installed DG count on a period of five years to reach its potential value. Figure 11 show that this scenario provides investors with greater certainty that the project is economically feasible as it takes into account incentives to improve the grid technical conditions.

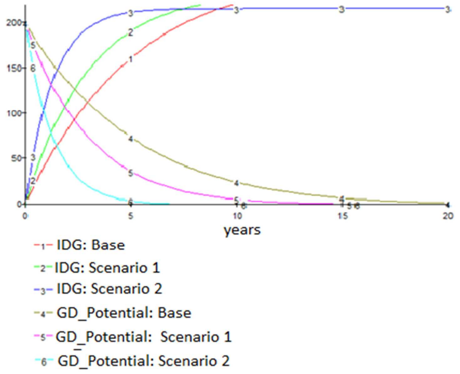

Figure 11. *IDG and DG_Potential over time in the base, scenario1 and scenario 2.*

The profitability shown in Figure 12 in scenario 2, compare with the profitability of previous scenarios, since the assumption was that the technical remuneration was based on, as previously mentioned, AGC ancillary service; a very high price for this reactive control service.

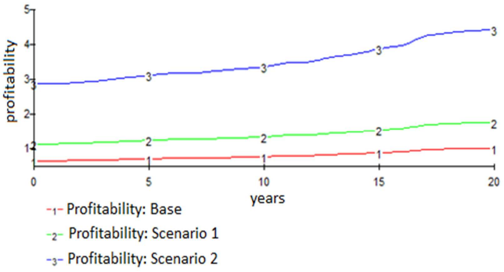

Figure 12. *Profitability over time in the base, scenario1 and scenario 2.*

CONCLUSIONS

Voltage and reactive control is an ancillary service of great importance in the operation, quality, and safety of a power system. An alternative for these services and worldwide used is Distributed Generation (DG). DG has proven efficient to increase voltage and to decrease active and reactive power losses within an interconnected area of influence. International experiences have shown that DG requires additional economic incentives to promote the diffusion, particularly in electricity markets where exists economies of scale.

This paper presents a system dynamic model to analyze the diffusion of DG in a Colombian power system operation zone. The model analyzes the effect of environmental and technical incentives in installed DG, and improves the voltage profiles and the reactive power flow in systems busbars.

The evaluation with the model shows that the environmental incentives improve profitability, but they are not sufficient to achieve a significant DG growth in the Colombian system. A feasible solution to improve the voltage control in Colombian power system is to convert DG into an active generation. In this case, to remunerate DG plants is important to include in the payment the technical incentives that are conditioned by the low voltages in the operation area and environmental incentives that are essential for plants with small capacities using renewable sources to achieve important developments to impact the Colombian generation park.

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