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A Study of incentives to increase the use of DG in Colombia based on a System Dynamics modeling

Estudio de incentivos para incrementar el uso de GD en Colombia basado en un modelado en dinámica de sistemas

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***Abstract*— This paper presents a study regarding the introduction of distributed generation (DG) within the Colombian power system by considering commercial, environmental and technical incentives. Environmental and commercial incentives were quantified by studying international precedents for implementing DG. Technical incentives were quantified by taking into consideration the remuneration received by generator agents providing automatic generation control (AGC), since this is the only ancillary service recognized in Colombia. A system dynamics model was built to evaluate the complete proposal. The study found that the current incentives proposed in Colombian regulation, such as tax breaks, are insufficient to cover total costs. Moreover, environmental incentives can be an efficient way of promoting renewable energy use in Colombia to achieve more generating capacity with lower pollution indices. Similarly, technical incentives, in conjunction with environmental incentives, can further improve DG growth in Colombia. The diffusion of DG thus becomes an additional tool for the operator of the interconnected system for controlling voltage and improving the quality and security of electrical power systems.**

***Index terms*— ancillary service, distributed generation, reactive power, system dynamics, voltage control.**

***Resumen*—Este artículo presenta un estudio de penetración de la Generación Distribuida (GD) en el sistema de potencia colombiano, teniendo en cuenta una propuesta de incentivos comerciales, medioambientales y técnicos.**

Los incentivos comerciales y medioambientales fueron cuantificados usando experiencias internacionales. Los incentivos técnicos se cuantificaron considerando la remuneración obtenida por los agentes generadores por prestar el servicio de control automático de generación, dado que este es el único servicio complementario reconocido en Colombia. Además, se construyó un modelo en dinámica de sistemas para evaluar la propuesta completa. El modelo muestra que los incentivos actuales en la regulación colombiana, tales como la exención de impuestos, son insuficientes en recuperar los costos de inversión totales. Los incentivos medioambientales pueden ser una opción eficiente para promover el uso de energía renovable en Colombia, con el fin de lograr más capacidad en generación con menos índices de polución, y los incentivos técnicos en unión con los ambientales pueden mejoraraún más el crecimiento de la GD en Colombia. Así, el modelo de difusión llega a ser una herramienta adicional para el regulador colombiano que permite estudiar políticas remunerativas relacionadas con el control de tensión y de esta manera mejorar la calidad y seguridad del sistema eléctrico de potencia.

***Palabras claves*— Control de tensión, dinámica de sistemas, generación distribuida, potencia reactiva, servicios complementarios.**

1. INTRODUCTION

Ensuring a secure electricity supply is now an important policy objective in virtually all modern economies (International Energy Agency, 2002). This objective deals not only with the availability of electricity but also with power quality. A power system operator must maintain frequency and stable voltage profiles within the required ranges (Bacon and Besant, 2001) and have technical support services (known as ancillary services) to satisfy such 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 a system's busbars using different equipment and technologies (Kirby and Hirst, 1997). This control is known as local control since reactive power can be supplied by demand, thus reducing the voltage drop at busbars and improving power quality indices (Kirby and Hirst, 1997).

Distributed generation (DG) is able to provide voltage control and a number of collateral advantages (Viawan and Karlsson, 2008). It helps to decongest transmission grids (Viawan and Karlsson, 2008) because it is located near consumption centres and also helps to generate or absorb the reactive power required by the system for the voltage in the nearby busbars to meet regulations. Regarding environmental issues, DG uses electrical plants having capacity below 20 MW and is able to use renewable resources, thus helping to

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reduce harmful emissions to the environment (Diaz, 2007). This paper presents a system dynamics diffusion model (Assil et al, 2008) for studying DG integration in the Colombian power system. The simulation allows DG growth to be analysed when trade, environmental and technical incentives are included in addition to the tax exemption incentives currently provided by Colombian regulations.

The study was conducted in a Colombian sub-region known as the coffee-growing region, which includes the departments of Caldas, Quindío and Risaralda (CQR). This region forms part of the south-western Colombian power system operating area and was selected for three reasons: there are voltage stability problems due to the connection of highly inductive loads (XM Compañia de Expertos en Mercados), DG seems to be a feasible solution for improving electricity quality and there is potential for DG due to the existence of water resources and raw material for biofuel production (Diaz, 2007).

This 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 sub-region of the Southwest operational area, Section 5 evaluates alternatives to the studied incentives to implement DG diffusion and Section 6 concludes.

2. TECHNICAL ASPECTS OF DG VOLTAGE CONTROL: A CASE STUDY

The Colombian power system voltage profile results from action regarding voltage sources (generating units and synchronous compensators) and voltage drops in transmission lines and transformers owing to reactive power transfers and reactive losses.

Voltage drop also depends on the type of load (Kundur, 1994; Stoft, 2002). Those involving electromagnetism, like motors and some fluorescent light ballasts, tend to use a lot of "reactive" power which causes voltage to drop (Kirby and Hirst, 1997). If such voltage drop is not corrected it affects all other loads in the vicinity (Bacon and Besant, 2001).

Voltage drop can be counteracted by injecting reactive power (Kundur, 1994); reactive power is very different to real power except that its description shares very similar mathematics. For instance, it can be supplied by capacitors which are entirely passive and consume no fuel. It can also be supplied by generators, generally at very low cost (Stoft, 2002).

Generator capacity for providing reactive power depends on machine coil excitation. When a generator becomes overexcited, it provides reactive flows to the system, whereas when excitation is low it absorbs a network's reactive flows. The capacity to maintain such reactive flow depends on limits concerning the armature current, field current and a machine's thermal limits (Kundur, 1994). Figures 1 and 2 present a capability curve showing the behaviour of the generators and the limits of reactive power generation and absorption regarding active power generation.

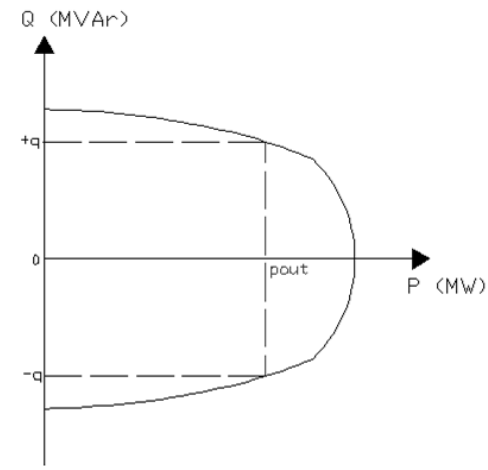

Figure 1. PQ Capability Curve of the Generator (Kundur, 1994)

A generator's capability curve is divided into positive MVAr values corresponding to the overexcited area and negative MVAr values corresponding to the underexcited area. Figure 1 shows that a generator can deliver reactive power flows (+q) for an active power out (pout) and absorb the remaining reactive power flows (-q) into the power system. When there are voltage problems in nearby busbars due to load variation, the generator should increase active power or reactive power absorption. Such reactive power variation in the generator terminals decreases the active power that is being delivered, as shown in Figure 2.

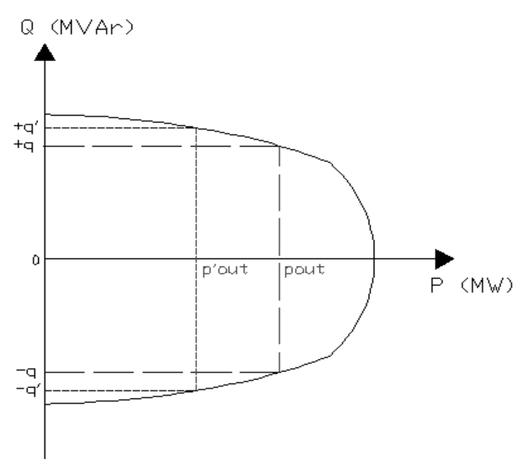

Figure 2. PQ Capability Curve of the Operating Generator (Kundur, 1994)

Voltage magnitude improves in the busbar connected to a generator; however, the generator reduces its active power production, as shown in Figure2. The generator decreases active power production because it is producing reactive power as technical support for voltages in the nearby busbars to improve the voltage profile.

Opportunity costs occur in this case due to the active energy flow loss that takes place in the generator when it delivers or absorbs reactive power flows. Generator agents should thus be paid to encourage them to help with grid support.

DGs can provide voltage control support service and the main research conclusions show that DG location has an important effect on voltage stability concerning its capacity (Nasser and Kurrat, 2009). Voltage stability should be taken into account as an objective when dealing with optimum DG allocation. Integrating DG at a certain feeder has no effect on the other feeders.

A. Case study

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

This system had voltage problems in busbars 19 and 22 which were connected to 33kV. There were five cases in the study taking into account the connection of 10 MW distributed generators in the busbars where voltage was beyond 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	Systemwithout DG
2	DGonly in busbar 22
3	DG busbar 22 and Capacitor banks
4	DGin busbar 19
5	DG in busbar 22, 19 and Capacitor banks
6	Only Capacitor banks

Figure3 shows voltage behaviour in busbars 19 and 22. Regulations require that the minimum voltage in a 33kV busbar is 0.9 p.u.(XM Compañia de Expertos en Mercados). In this system, busbar 19 had 0.6pu voltage. The voltage increased to 0.97 when it was connected to DG, thus complying with regulations. When capacitor banks (CB) were connected the result was 0.98, thereby improving magnitude but with no substantial change. In case five, voltage increased to 0.7p.u.,showing the need to implement DG due to the fact that even though CB gave the same magnitude as the distributed generator, it did not increase voltage in busbar19 in the same proportion.

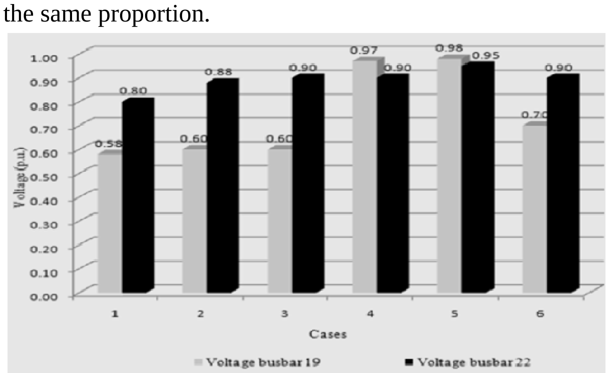

Figure 3. Voltage in busbar 19 and 22

Figure 4 shows how electrical loss magnitudes became reduced by more than 80% when DG was installed on nodes having low voltage problems. Losses decreased proportionally to increased voltage in the busbars having problems (cases three and four). DG thus provided local control with regional implications. The most visible consequences were voltage increase, line decongestion and loss reduction.

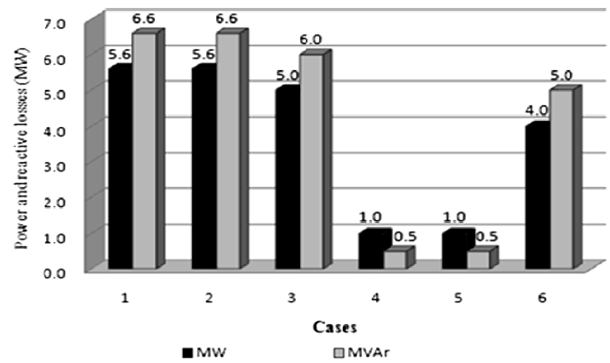

Figure 4. Losses of Active and Reactive power in the lines between busbars 17 and 19

3. ECONOMIC ANALYSIS OF DG DIFFUSION

Beforethe development of the system dynamic model, DG diffusion was analysed from an economic perspective which provided information about operation and investment costs when implementing DG. DG was analysed with organic materials to produce biofuel; these plants are expected to be beneficial in terms of reducing pollution indices (International Energy Agency, 2007). Furthermore, Colombia has begun to develop successful projects for biofuel production due to its agricultural potential, e.g. involving sugar refineries and African palm planatations.

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

The levels of investment and the average generating costs for different technologies are compared in (International Energy Agency, 2007). It also gives a projection that alternative energy generation will reduce investment and generating costs within 20 years because its use will be increased worldwide.

Current DG projects' capital costs using biomass are high compared to the costs incurred by centralised conventional generation projects(International Energy Agency, 2002). It is thus essential to provide economic incentives to increase this type of generation.

The experience of countries such as Spain, the USA and Germany has shown that incentives are crucial (Iberdrola, 2011), especially during the initial construction and operation period. Medium-term incentives are important for increasing the number of distributed plants for using them as a complement for interconnected system operation, thus creating an additional voltage control tool.

Economic incentives for DG can be justified because they can be used to improve power quality by providing ancillary services (Nasser and Kurrat, 2009). DG also helps to postpone additional labour in transmission and distribution systems because surges in system loads become reduced, thereby allowing the use of conductors having the same calibre and transformers, protectors and generators having the same capacity (Kundur, 1994).

DG also has the potential to use a broad range of renewable and non-renewable technologies (Rodriguez, 2009). This not only benefits the environment but also provides greater flexibility and a greater reserve margin for increasing reliability during periods of drought and also in times of fossil fuel supply shortage and price volatility.

The main barriers to DG diffusion in Colombia are costs and the fact that incentives are only available during the investment period and are indirect because they are based on tax exemption given to plants which are being constructed (Rodriguez, 2009).

It was thus proposed to test the effect of environmental incentives for operation as well as technical incentives related to voltage and reactive control as a DG diffusion mechanism in Colombia.

4. A MODEL FOR PROMOTING DG USE IN COLOMBIA

Electric industry deregulation introduced decentralisation and competition (Hunt and Shuttleworth, 1996). Decentralisation increases system operation complexity because before, in a regulated system, utilities were vertically integrated and cooperated voluntarily to operate a reliable system by coordinating their resources with neighbouring utilities (Chaoand and Huntington, 1998) in the knowledge that regulated tariffs would cover bundled costs (Kirby and Hirst, 1997). With deregulation, a 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, pp.62-69). However, system operators' legal responsibilities must be clearly defined by new regulations (Gómez, 2003).

A major objective of electricity deregulation is to achieve a workably competitive wholesale market (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 concerning deregulation: demand responsiveness to price variation and new investment in generation resources (Hunt and Shuttleworth, 1996).

Larsen and Dyner(Larsen et al, 2004, pp.1767-1780) have shown that uncertainty and 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 construct models helping understand the dynamic path into the future. Among the tools that are useful for strategy formulation in utilities and which need to be applied after deregulation is the business dynamics or the system dynamics (SD) model.

SD has been used in the deregulated electricity sector for analysing investment in generating electricity (Ford, 1999; Kadoya et al, 2005; Arango, 2007). It has also been used in studies of competition between generating plants that use different primary energies (Quadrat and Davidsen, 2001, Botterud et al, 2002, pp. 1-7) and studies on including alternative energy in decentralised markets (Ford et al, 2007, Zuluaga and Dyner, 2007).

The model was inspired by the Bass classical diffusion model (Bass, 1969). This model was adapted to system features, in particular the use of DG integration regarding different incentives in place and proposed for this technology. This research presents the dynamic hypothesis for the model and then the formal model.

A. Dynamic hypothesis:

The feedback loop diagram reported in Figure 5 represents the dynamic hypothesis for DG diffusion. It shows the main variables and its relationships for analysing DG diffusion in the Colombian power system, taking additional incentives into account. Note that this approach has been designed for a particular region instead of a whole system, i.e. the CQR area (see section 2).

The main force driving DG is investment, so that increased investment increases installed DG capacity, following a delay. The Colombian power system has a market-orientated structure, which means that investment is driven by their profitability.

Profitability is increased by endogenous incentives, such as technical and environmental incentives, as well as exogenous incentives which are the regulatory incentives. Environmental incentive is justified by the fact that there is CO^2 and NOx reduction since such generation has lower environmental impact compared to large central power systems (International Energy Agency, 2007).

The second incentive is aimed at using DG as a tool for providing power system support services, specifically to pay distributed generators to help maintain voltage and reactive levels within the required ranges to improve quality and safety indices.

Technical incentives are limited due to transmission systems' operational constraints. In particular, an inordinate amount of DG can cause electrical imbalance at any point within an interconnected transmission network leading to immediate and severe repercussions on electricity quality and deliverability throughout the whole interconnected grid.

The model also takes into account existing regulatory incentives. There have been tax exemptions on sales from alternatives energies (wind and biomass resources) in Colombia for 15 years. To justify such exemption, generators are required to hold carbon emission certificates and invest fifty percent of such certificates in social infrastructure projects (Law 788, 2002). Once in full operation, the generating agents do not receive any type of remuneration or additional bonuses for the use of renewable or low environmental impact resources.

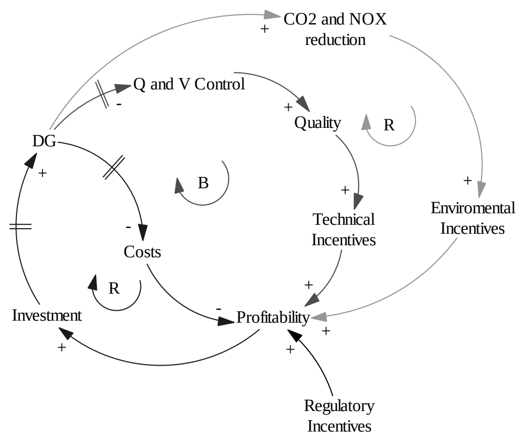

Figure 5.The feedback loop diagram - DG diffusion.

B. Formulation of the simulation model:

The feedback diagram in Figure 5 becomes a formal visual diagram at a more detailed (operational) level, which distinguishes between stock variables (i.e. state variables) and flow variables (or rates) [30].

This type of mapping is shown in Figure 6. The visualisation used is taken from one of the specialist simulation softwares available for this type of simulation; stocks accumulate resource flows and characterise system memory. Stock variables (boxes) can only change when the associated flows change. The stock and flow diagram provides the structure for the actual mathematical formulation underlying the model. The main stock or state variables of the model are distributed generation potential (DG_potential) and installed distributed generation (IDG), as seen from the macrostructure of the model sketched in Figure 5. The level of each state variable is defined in terms of associated flows. The model's formulation takes into account a pre-investment phase, an investment phase and the operating phase.

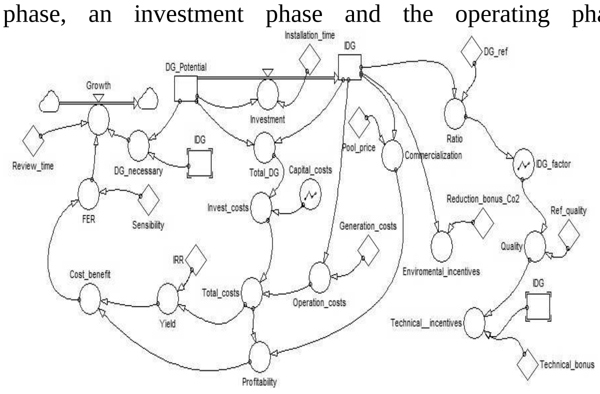

Figure 6. The formal diagram - DG diffusion

The pre-investment phase is represented in the model by variable flow growth which culminates when the final evaluation is made and the decision to invest is made. Equation (1) shows variable growth behaviour and its relationship with other system variables. It is also necessary to consider that growth is conditioned so only installed DG grows to the referred MW and thus guarantees a real answer.

This growth is restricted by an evaluation between the distribution system regulator and operator to determine the necessary DG according to each region's characteristics to ensure proper system functioning within the technicalities that arise in the area where DG is to be installed. The study carried out by these agents is determined by the evaluation time corresponding to the time required to evaluate the technical conditions of the busbars connected to DG.

$$growth = MAX\left(\frac{FER \times DG\_necessary}{Review\_Time}, 0\right) \qquad (1)$$

The investment decision depends on profitability, which is represented by financial evaluation results (FER). Equation (2) defines FER as a function of cost_benefit analysis in the market taking into account a variable called price sensitivity (α) to demand/supply balance; this variable represents the dynamics of disequilibrium price behaviour.

$$FER = Cost\_benefit^{\alpha} \qquad (2)$$

Clear understanding of the conditions regarding the project to be evaluated is required in investment analysis of DG installation. Evaluating profitability alternatives should be complemented by a detailed analysis of quantitative aspects, which takes time while evaluations are performed and decisions are made by the investors.

Profitability is expressed as the cost-benefitratio offered by developing and implementing the project. In other words, if the project is profitable, this factor will have values greater than one, thus directly affecting investment in DG power plants. The marketing of active power (P) by DG agents is the benefit analysed in this case.

The evaluation of DG growth allows DG_potential to grow into DG plants connected to the Colombian power system.

DG potential level in the formal model is fed by attractiveness flow which compares growth to internal rate of return (IRR) and the outcome of this level converges into the variable investment flow, representing the project's second development phase.

The last phase is the operational phase which is more evident because of installed distributed generation (IDG). These IDG plants include the built plants' capacity in MW.

These IDG plants receive remuneration from the different incentives implemented in the DG diffusion model. The differential equations associated with the above are:

$$\frac{\partial DG\_potential}{\partial t} = -Investment \quad (3)$$

$$\frac{\partial IDG}{\partial t} = Investment \quad (4)$$

$$Investment = \frac{IDG}{installation\_time} \quad (5)$$

Equations (3) and (4) represent system levels. These variables are represented by differential equations since pertinent information changes as time elapses, adjusting to the different conditions represented in each input and output flow.

Investment, installation and DG operational costs must be analysed to perform the feasibility study. The equations associated with costs are:

$$Total\_costs = Invest\_cost + operation\_costs \quad (6)$$

Total costs are the sum of the main costs associated with DG implementation, i.e. DG power plant investment and operating costs. Investment costs are biomass plant capital costs incurred when implementing the plant in any point of the system.

$$Invest\_costs = Total\_DG \times Capital\_costs \quad (7)$$

The capital costs defined in equation (7) are set according to (International Energy Agency, 2007), since the DG used corresponds to generators using biomass (i.e. biofuel in this case). Further acceptance of this method is expected, which will decrease costs and achieve efficiency and consumption improvement. Capital costs are thus a decreasing table function.

Operating costs are associated with generator needs; in other words, operating costs depend on the amount of power generated. Biodiesel plant operating costs are thus taken from generation costs (International Energy Agency, 2007) and biodiesel plant operating costs are described in equation (8).

$$Operation\_costs = IDG \times Generation\_costs \quad (8)$$

The sale of P in DG is based on plants having installed power lower than 20 MW and is described in equation (9) using non-centralised dispatch. The price paid to each generator is the power pool price (Rodriguez, 2009).

$$Commercialization = IDG \times Pool\_price \quad (9)$$

The pool_ price is taken from XM records, the organisation in charge of the Colombian electricity market, to calculate the fee they are paid for participating in the electricity market (XM Compañia de Expertos en Mercados).

Environmental incentives are evaluated by air quality measuring the amount of greenhouse gases emitted into the environment at the time of generation, especially when fossil fuels are used.

$$Enviromental\_incentives = IDG \times Reduction\_bonus\_CO_2 \quad (10)$$

Equation (10) defines the remuneration for CO^2 and NOx reduction and is given by the reduction bonus and installed DG capacity.

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, this being a favourable situation while not exceeding the regulatory ranges which depend on voltage level.

DG magnitude reference was found for this case corresponding to the number of MW of installed DG that can be connected to an electrical grid prior to causing quality problems such as fluctuations in nominal busbar voltage values, voltage collapse, amongst other quality problems associated with voltage waveform.

System quality at a given time might be known by using the result of the IDG factor. Such quality must be adjusted to regulatory voltage values because this value is compared to the quality_reference. Equation (11) shows that quality with IDG_factor and the quality_reference have been included in the simulation model.

$$Quality = IDG\_factor \times Ref\_Quality \quad (11)$$

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

$$Technical\_incentives = IF(103.5 < Quality < 126.5, IDG \times Technical\_bonus, 0) \quad (12)$$

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

5. EVALUATION.

This section evaluates the proposed incentives. The base scenario considered existing indirect incentives and the sale of generated energy at stock market prices. The simulation experiments led to observing the effect on the Colombian electrical power system.

A. *Base Scenario*

The base scenario was the worst scenario because it only considered indirect incentives such as income tax and interest rate exemption.

The benefit was annual remuneration for MW sales; the model used the actual price paid per MW in bilateral contracts because these plants have lower than 20 MW capacity and, according to Colombian regulations [33], these plants are not obliged to participate in daily auctions.

Figure 7 shows the IDG and the DG_potential for the base scenario. It shows steep growth in the first half and smooth in the second half, which is a goal seeking behaviour where IDG reaches the needed amount of DG.

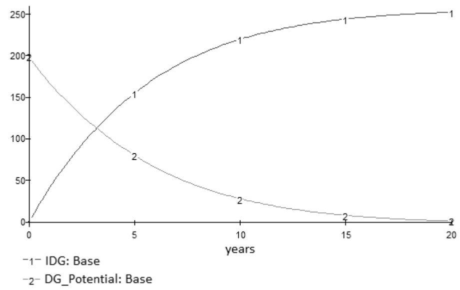

Figure 7.IDG and DG_potential evolution over time in the base scenario.

Figure 8 shows the behaviour of profitability, defined in this model as cost-benefit ratio. The project is attractive from the financial point of view when this ratio is greater than 1. Therefore, the base scenario shows that even though profitability may increase in 20 years, it does not overcome the unit threshold; the project was thus not financially justified.

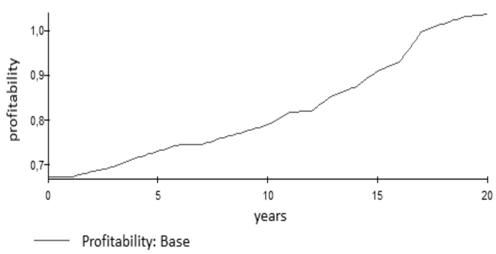

Figure 8. Profitability over time in the base scenario

B. Scenario 1

The first analysis scenario was characterised by incorporating environmental incentives. These were given due to reduced emission of greenhouse gases such as CO^2 and NOx.

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

The bonus system or feed in tariffs has been successful in Germany, where premiums vary according to type of primary energy used, ranging from \$ 5 per MWh to \$ 15 perMWh(Huacruz, 2000); these incentives are 1 cent per kWh in the USA (Hammonsand and Boyer, 2000). Rates are set in China according to the average price of coal in the relevant province, with a premium of about 3 cents per kWh (Denneand and Waikato, 2006).

Figure 9 shows IDG development. IDG reached DG reference value faster with environmental incentives in only 10 years compared to base scenario.

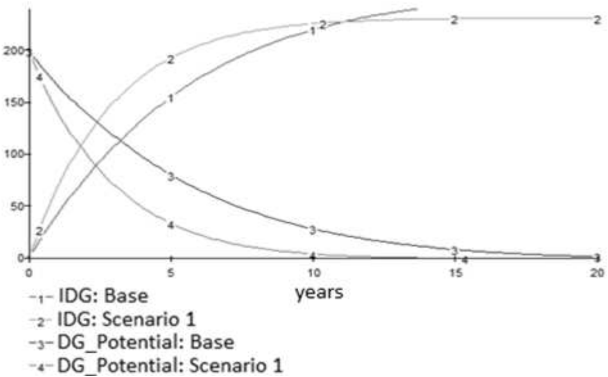

Figure 9.IDG and DG_Potential evolution over time in the base and scenario1.

Figure 10 shows that projects benefiting the environment and receiving financial remuneration had income or profits greater than costs, and a profitability value greater than one. Profitability grew over a 20-year period compared to the base scenario, indicating that incentives will trigger investors to think of this type of generation.

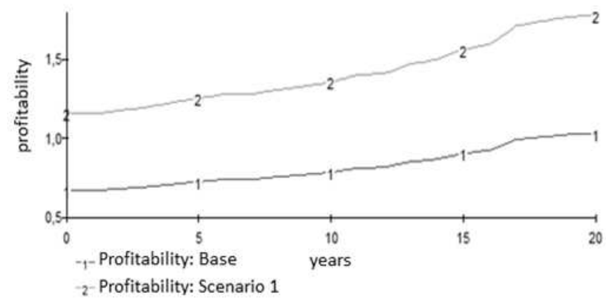

Figure 10. Profitability over time in the base scenario

C. Scenario 2

All scenario 1 characteristics in addition to the modelling of technical incentives were taken into account when implementing scenario 2. This scenario had the most favourable behaviour since installed DG plants had a five-year period to reach potential value. Figure11 shows that this scenario provided investors with greater certainty that the project would be economically feasible as it took into account incentives to improve the grid's technical conditions.

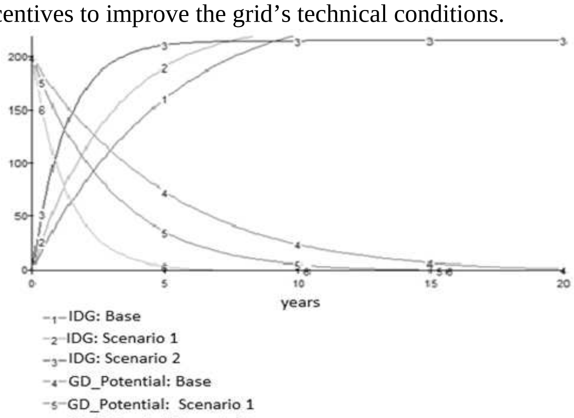

Figure 11.IDG and DG_Potential over time in the base, scenario1 and scenario 2.

The profitability shown in Figure 12 in scenario2, compared to the profitability of previous scenarios, since the assumption was that technical remuneration was based on AGC ancillary service, this being a very high price for such reactive control service.

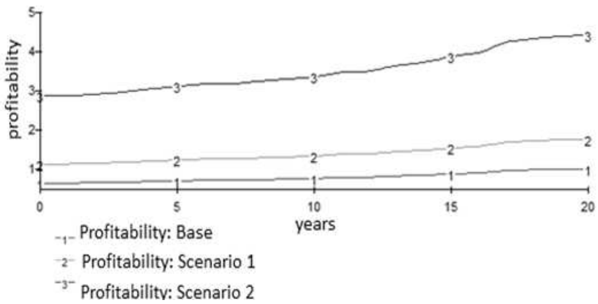

Figure 12.Profitability over time in the base, scenario1 and scenario 2.

6. CONCLUSIONS.

Voltage and reactive control is a very important ancillary service in power system operation, quality, and safety. Distributed generation (DG) is an alternative for these services which is used worldwide. DG has proved efficient in increasing voltage and reducing active and reactive power losses within an interconnected area of influence.

International experience has shown that DG requires additional economic incentives to promote diffusion, particularly in electricity markets having economies of scale.

This paper has presented a system dynamic model for analysing DG diffusion in a Colombian power system operating area. The model analysed the effect of environmental and technical incentives in installed DG and improved voltage profiles and reactive power flow in system busbars.

The evaluation with the model showed that environmental incentives improved profitability but were not sufficient to achieve significant DG growth in the Colombian system.

A feasible solution for increasing DG use in the Colombian power system would be to remunerate DG plants, including a payment due for technical incentives conditioned by low voltages in the operation area and environmental incentives essential for small capacity plants using renewable sources to ensure increasing the portfolio of technologies used to generate electricity in Colombia.

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