



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

IMPACTO ECONÓMICO DE LA GENERACIÓN DISTRIBUIDA FOTOVOLTAICA EN REDES DE DISTRIBUCIÓN ELÉCTRICA

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Tesis para optar al grado de
Magister en Ciencias de la Ingeniería

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don Hugo, que me apoyaron a lo
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RESUMEN

La aparición de elementos de generación en redes de distribución eléctrica presenta un cambio de paradigma respecto a cómo se diseña, regula y opera este segmento de los sistemas eléctricos de potencia. En esta tesis, se cuantifica el potencial impacto económico que genera la inclusión de generación distribuida (GD), específicamente paneles fotovoltaicos (FV), en redes de distribución eléctrica de tamaño real bajo esquemas regulatorios existentes en el mundo. También se calcula el costo incremental de aumento de capacidad de la red eléctrica, de manera de satisfacer las condiciones térmicas de operación de los elementos serie (conductores y transformadores) a lo largo de la red, utilizando como base redes diseñadas para satisfacer la demanda máxima de un período regulatorio tipo de evaluación de cuatro años sin generación distribuida. Para abordar la problemática se propuso y desarrolló una metodología de simulación de la operación horaria de compra y venta de energía eléctrica en redes de distribución mediante flujos de potencia trifásicos balanceados sujeto a restricciones de voltaje y capacidades térmicas de elementos serie. Al ser activada la restricción de capacidad térmica, se utiliza un algoritmo de reemplazo del elemento serie en cuestión por un elemento de mayor capacidad, entregando así señales económicas de costos por aumento de capacidad. Sobre este motor de cálculo de flujos de potencia horario se analizan múltiples escenarios de penetración de GD utilizando sorteos aleatorios de instalación de paneles FV, parametrizando el comportamiento de los clientes, es decir, el ratio potencia instalada FV-demanda máxima cliente [kW/kW], proceso que nos permite de forma *ex post* medir la eficiencia con la cual un esquema tarifario puede acotar el impacto

económico de la GD. Los resultados indican que bajo esquemas tarifarios del tipo volumétrico la empresa de distribución percibe pérdidas de utilidad bajo escenarios extremos técnico-factibles del orden de 80 %, un 6 % en caso de utilizar tarifas que cobran capacidad de forma fija y disminuyendo a 5 % bajo esquemas tarifarios propuestos del tipo “comprar todo-vender todo”, que distinguiendo el rol de consumidor y generador del cliente. El costo social energizado de no modificar las utilidades de la empresa de distribución alcanzan valores entre 1.3 y 4.5 US\$/MWh bajo esquemas de tarifas que cobran capacidad de forma fija y entre 0.9 y 3.0 US\$/MWh para tarifas que distinguen los roles de consumo y generación. Como aporte regulatorio se cuantificó el impacto del reconocimiento de pérdidas evitadas de las inyecciones de energía, abriendo un flanco para mejorar la regulación actual del segmento de distribución eléctrica, permitiendo así dar señales horarias para los recursos energéticos distribuidos (RED).

Palabras Claves: Generación Distribuida, Energía Fotovoltaica, Distribución Eléctrica, Regulación de Mercados Eléctricos, Tarificación Eléctrica, Sorteos de Monte Carlo, Adaptación Económica de Redes de Distribución Eléctrica, Selección Óptima de Conductores

ABSTRACT

The appearance of new power generation agents at the distribution network presents a paradigm shift on how to design, regulate and operate this segment of the electric power systems. On this thesis, the potential economic impact of the distributed generation (DG), specifically photovoltaic panels (PV), is quantified, under already worldwide existing regulatory schemes. Incremental network capacity costs due to thermal constraint violations of series elements (transformers and conductors) are also calculated, starting with a base distribution network designed to withstand the demand growth during a typical for your regulatory period without considering DG penetration. In order to assess this problematic an hourly three-phased power flow simulation methodology was proposed and developed under voltage and electric series elements thermal capacity constraints. When activating the latter constraint, a series element upgrade algorithm is executed, which ensures an economical upgrade of the overloaded element and gives economic signals of incremental network capacity costs. Multiple random DG penetration scenarios are analyzed using the proposed power flow calculation engine, parameterizing the behavior of the clients, this means, the PV installed capacity-Customer Max Demand ratio [kW/kW], process that allows us to *ex post* measure the efficiency with which a tariff scheme may limit the economic impact of DG. Results indicate that under volumetric tariff schemes the distribution network operator (DNO) can suffer, under extreme penetration scenarios, up to 80 % of profit loss, a 6 % under fixed capacity charge tariff schemes and up to 5 % under proposed *buy-all sell-all* tariff schemes, being the latter a scheme that distinguishes the customer

as an electric consumer and generator. The energized social cost of not having an impact on the DNO profits (business as usual) can a value up to 1.3 and 4.5 US\$/MWh under fixed capacity charge tariff scheme, and between 0.9 and 3.0 US\$/MWh under tariffs which distinguish the consumption and generation roles of a customer. The economic impact of acknowledging avoided energy losses for the power injections was calculated, opening a new flank of discussion on how to regulate the distribution segment of electric power systems, specifically on giving temporary economic signals to the distributed energy resources (DER).

Keywords: Distributed Generation, Photovoltaic Energy, Electric Distribution, Electricity Market Regulation, Electric Tariffication, Monte Carlo Sorting, Economic Adaptation of Electric Distribution Networks, Optimal Conductor Size Selection.

1. INTRODUCTION

Electricity markets have experienced major changes in the last three decades. Firstly due to the liberalization of the market in the 80s followed by environmental concerns which have prompted renewable energy resources as a new agent on the market. Apart from these factors, the drop in solar photovoltaic (PV) prices along with power electronics advances have improved the technical and economic feasibility of home rooftop solar PV generation, which has led to a larger presence of these devices in the electricity market. Add to this equation lower battery prices, and the result is active distribution networks that generate or manage part of their own consumption with distributed energy resources (DER). These active distributed elements modify the operation of the network from its original, static planned operation to an active, multi-state network. This new form of operation introduces more agents to the market, opens possibilities for new ancillary services and cleans the energy matrix by generating power by means of renewable energy sources. However, it also brings new technical problems, such as voltage control, new fault protection schemes, connection standards and new electric distribution regulation that must be assessed by regulators and the academic world.

1.1 Problem definition

Given the development of new technologies of electric power generation, regulators are facing a new challenge on how to incorporate these devices and new agents into a pure consumptive distribution network market, in order to minimize the impact that lower consumption or even generation from clients has on the distribution network operators (DNO's). This work addresses this problem by analyzing the economic impact of rooftop

PV connected to the lower voltage part of real size distribution feeders by quantifying the capital expenditure that the DNO's have to incur in order to meet thermal thresholds throughout the system (lines and transformers) and also measure the change in profits by analyzing the economic operational model of distribution companies, paying special attention on the revenue and cost structure that the DNO's have under a given regulation. This process is fundamental for understanding the dynamics of capital expenditure and operational profits of distribution companies which is the base for developing a sound regulation that could promote benefits for the distribution companies and consumers.

1.2 Structure of the thesis

The thesis aims at analyzing the short term future of distribution networks with the addition of DER's, specifically PV distributed generation (DG), as an effort to understand and quantify the impact of this new technology at the distribution feeder networks, paying attention on the impact at the quality of the electric product (voltage), use of the networks capacity (current) and the economic impact on the operation of the DNO, by simulating the use of actual tariff schemes. This last exercise is an effort to give better regulatory signals for a regulatory exercise that was never designed to have active generation at the costumer side of the meter and hopefully help for future research on the related matter.

The thesis is organized as follows: Chapter 1 introduces the problematic of new agents entering the market which modify the revenue and cost structure of the classic DNO economic operation. Chapter 2 defines the concept of DG that is used for this work and contextualizes the Chilean electric market, paying attention on the regulation of the

distribution section, making parallels with the actual regulation on other countries, such as Germany and Spain, which have dealt with DG for a longer period of time and have already come up with regulatory schemes. A glimpse of Chilean and Spanish tariffs is done, detailing how the tariffs schemes at this European country have evolved during the last years, because of the penetration of DG.

Chapter 3 discusses the nature of distribution networks and how they are designed, operated and remunerated. This chapter also exemplifies the technical impact of DG on the use of system and quality of the electric product delivered to the end consumers. It ends by explaining the process of modeling of distribution network and the concept of line loss compensation using tap changer at the feeder's header.

Chapter 4 presents the methodology of the proposed model that is used to analyze the technical and economic impact, detailing the input parameters, assumptions and the study cases that this work addresses.

Chapter 5 presents the obtained results from different points of view and analyses them, both technical and economical.

Chapter 7, 8 and 9 discuss the limitations of the scope of the work, how it could be improved for future works and which conclusions can be drawn from the work, followed by recommendations in the line of the conclusions.

2. CONTEXT

High electricity prices and lower PV costs are promoting the entrance of this technology at the distribution level of the electricity market. With this happening, the regulator has to go on ahead in the realm of distribution regulation, because in the years to come the probability of having rooftop solar power generation is high. In addition, the population is starting to actively oppose to large hydro and coal plants. The examples are Endesa and Colbun's Hidro Aysen and the Suez Energy's coal plant Barrancones. These decisions, along with the four year drought that the Chilean electric system has been suffering, have pushed electricity prices up, reinforcing a close future with rooftop solar generation.

2.1 Definition of distributed generation

Throughout the years, different authors and entities have presented their definition of distributed generations, which range from general, to more specific. The U.S. Department of Energy ascribes a general definition: any small, modular electricity generator sited close to the customer load is considered distributed generation. CIGRE, on the other hand, presents a more specific definition: a non-centrally planned and dispatched power generation technology that is usually connected to distribution networks and smaller than 50 MW. Lastly, and even more specific, the International Energy Agency states that any generation plant serving a customer onsite or providing support at a distribution network and connecting to the network at distribution level voltages [14] is considered to be DG.

The definition of DG is an important issue, because of the implications that biased definitions could have in the regulative process for this kind of generation. Poorly made regulation could create entry barriers that could perpetuate the power market that big utilities have.

2.2 Distribution network regulation with embedded generation

The electricity distribution business is considered to be a natural monopoly due to its economic characteristics. This obligates the state to regulate its operation and motivate the sufficiency, safety and economical operation of the distribution company. This regulation takes different forms around the world, but the majority has something in common. Most of them are based on Performance Based Regulation methods [15], which motivates firms to earn more than what they were expected by means of efficiency in investments and operations. Some examples are the price cap method, which regulates the price of the given service or product [13, 16], and revenue cap, a method that limits the incomes that a company can have during a fixed period of time [17]. Both methods tackle the problem in a static way, and should be updated every 3 to 5 years in order to correctly represent the cost structure of the service of the distribution companies and changes in technology. These regulative incentive methods can be pushed even further, adding specific industry related incentives, such as loss reduction incentives [17] currently used in Spain. Several countries still have static oriented distribution regulation that doesn't behave well under the presence of distributed generation. These frictions appear because of the unsolved questions of capacity related cost allocation, use of system payments and energy surplus selling price schemes.

The following section outlines current regulatory environment in Chile and worldwide.

2.2.1 International Regulation

Germany and Spain are at the forefront of regulation of distribution systems with embedded generation and are good examples of different ways to tackle the generation issue.

2.2.1.1 Germany

Germany uses a revenue cap method approach with a benchmark company for limiting the incomes of the distribution companies. This exercise is done for every existent distribution company in Germany (around 900). The distribution company can recover any capacity related investment that is needed for a load or generator connection and these costs are socialized and charged in a postage-stamp way for each voltage level throughout the loads. Distributed generators do not pay use of system charges; they only pay shallow connection point costs. Loads pay an annual based power charge for their maximum consumption and energy charges for volume of consumption. The participation of clients in the system peak demand is calculated using coincidence factors.

Distributed generators are compensated for higher voltage avoided costs, i.e. transmission costs, unless they are being subsidized under a feed-in-tariff. These feed-in-tariffs are part of the Renewable-Energy-Act, or *Erneuerbare-Energien-Gesetz*, that promotes renewable energy generation.

2.2.1.2 Spain

Spain uses a modified profit cap method, which fixes the remuneration of the company for a given regulatory period using a reference company model. This model maps the concession areas of electric distribution and creates a network that connects the end users to the transmission system, [12] fulfilling technical constraints in an economically efficient way. The remuneration of the DNO's takes into account the investment, operation, maintenance and other costs such as commercial management, network planning and energy management costs. Explicit loss reduction incentives are given in order to increase profits. There is no geographical differentiation in tariffs, neither for demand nor generators. Tariffs are the same for every client connected at a certain voltage independent of the characteristics of the network that they are connected to. Load costumers are charged with these tariffs for commercial costs in a fixed monthly scheme, for power for the contracted amount of kW's (US\$/kW/month), whose cost is updated twice a year, and for energy, a monthly volumetric scheme (US\$/kWh). Low voltage load customers under 15 kW of contracted power can choose from different tariffs, ranging from flat to two and three periods of energy pricing with a flat power tariff (Table 2-1). Load costumers with contracted power higher than 15 kW can only op for a single three period tariff (Table 2-2).For higher voltage user tariffs, range from three to six periods. Table 2-3 shows the three period medium voltage tariffs. Annex 7 shows the hours of coverage of the different Period of each presented tariff presented by Iberdrola.

Table 2-1: Low voltage Spanish tariffs with one, two and three periods for clients with contracted power lower than 15 kW

Tariff	Application	Tp [€/kW/Year]	Te [€/kWh]			
			W.O.	Period 1	Period 2	period 3
2.0A	$P_c \leq 10 \text{ kW}$	38.0	0.0440	-	-	-
2.0DHA	$P_c \leq 10 \text{ kW}$	38.0	-	0.0620	0.0022	-
2.0DHS	$P_c \leq 10 \text{ kW}$	38.0	-	0.0620	0.0029	0.0009
2.1A	$10 \text{ kW} \leq P_c \leq 15 \text{ kW}$	44.4	0.0574	-	-	-
2.1DHA	$10 \text{ kW} \leq P_c \leq 15 \text{ kW}$	44.4	-	0.0746	0.0132	-
2.1DHS	$10 \text{ kW} \leq P_c \leq 15 \text{ kW}$	44.4	-	0.0746	0.0178	0.0066

Table 2-2: Low voltage Spanish tariff with three periods for clients with contracted power higher than 15 kW

Tariff	Application	Tp [€/kW/Year]			Te [€/kWh]		
		Period 1	Period 2	period 3	Period 1	Period 2	period 3
3.0A	$P_c \leq 15 \text{ kW}$	40.7288	24.3733	16.2916	0.018762	0.12575	0.00467

Table 2-3: Medium voltage Spanish tariff with three periods

Tariff	Application	Tp [€/kW/Year]			Te [€/kWh]		
		Period 1	Period 2	period 3	Period 1	Period 2	period 3
3.1A	$1 \text{ kW} \leq V \leq 36 \text{ kW}$	59.1735	36.4907	8.36773	0.014335	0.012754	0.007805

The Spanish regulator doesn't recognize the DG related incremental capacity costs [11], so generators have to pay the entire connection costs that their operation produces at the network. This capacity related cost recovery scheme is known as deep connection charges scheme.

2.2.2 Chilean Regulation

The Chilean regulation of distribution companies uses a price cap scheme that fixes the tariffs for the high and low voltage regulated consumers. To do so a yardstick or benchmark company is created from scratch to connect the end consumers to the transmission system [13]. This network has to satisfy economic, security and technical standards. In order to make a fair comparison and to give geographical signals, all the national distribution companies are statistically analyzed in order to understand their consumer density profiles, total length of network, amount of energy sold to clients and other indices. Afterwards, the distribution companies are grouped using a similar economical operation criteria based on the statistical analysis. From each group a representative distribution area is analyzed in order to calculate the parameters that would later on be translated into tariffs. Load customers can choose how their peak demand is measured. The options range from a fully energized tariff, where power and network costs are charged as a function of energy consumption, passing through a fixed contracted power tariff, finishing with a measured participation during peak demand hours of the system. These power and capacity charges are calculated as a postage-stamp, averaging the cost of power with the participation of the clients using coincidence factors.

The regulator recognizes average energy and power losses that the model enterprise has, thus implicit incentives are given on loss reductions, because tariffs are constructed charging average energy and power losses, which means that an extra profit gap can be incorporated during the regulatory process by means of optimal operation.

The 2012 “Net metering law” [10] (now known as the net billing law) defines the connection charges as every modification that has to be done to the network as a result of the connection of a generator. It also defines the energy price paid for the surplus distributed generation that is injected back to the network, where its value is the same price of energy at which the client buys energy from the DNO plus the average avoided energy losses. In other words, this is a deep connection charge scheme, with no use of system charges apart from the ones paid as a consumer.

The technical standard guide, which comes in hand with the law, is being built in order to avoid inverse power flows at the medium and low voltage interface (distribution transformers). This means that the impact of DG, in terms of power flows, is trying to be kept at low voltage levels of the network. One of the regulatory restrictions that are being considered to isolate this impact is measuring the minimum demand at each distribution transformer and limiting the sum of power generation capacity downstream to that value.

2.3 Tariffs

Tariffs are the tangible part of the regulation process for the end consumers. They get charged depending on the contracted tariff by a mixture of energy consumption (kWh per month) and capacity consumption (kW per month). The percentage of energy and power charges depends on the legislator assumptions. In Spain, for example, the legislature created several tariff options with a mixture of power and energy components to recover the capacity investments, where the weight of each component depends on the connection voltage and the size of the client. This power to energy ratio of distribution

capacity charges has changed throughout the years, starting from a more energized fashion, following a trend towards a more "*powerized*" charge [18]. These changes in capacity related costs recovery are shown Table 2-4:

Table 2-4: Percentage of capacity related investment recovery for Spanish distribution companies

Tariff Group	Distribution			
	2012 New Proposal		2001 Methodology	
	Tp	Te	Tp	Te
2.0 A	91.4%	8.6%	43.7%	56.3%
3.0 A	84.8%	15.2%	43.7%	56.3%
3.1 A	84.4%	15.6%	24.6%	75.4%
6.1	79.3%	20.7%	24.6%	75.4%
6.2	83.5%	16.5%	43.9%	56.1%
6.3	84.0%	16.0%	57.3%	42.7%
6.4	82.1%	17.9%	80.0%	20.0%

The Chilean case presents different types of tariffs, firstly categorized for voltage connection (high and low), followed by different options, ranging from fully energized tariff (low voltage BT1), passing through intermediate tariffs with contracted, limited maximum power (high and low voltage AT2 and BT2), continuing to a measured power charged tariff, which charges for the highest power integrated every 15 minutes (high and low voltage AT3 and BT3), finishing with a contracted and measured power charged tariff during peak demand of the global system (high and low voltage AT4 and BT4) [19]. The fully energized tariff (BT1) represented, in 2005, the 97 % of the regulated users in Santiago, the capital of Chile.

The U.S., with its 50 regulatory State commissions, presents simultaneously several electric regulatory processes over the country, maybe thousands considering the number

of utilities. Most of them work under the fully energized tariff scheme, which charges energy, power and capacity as a function of energy consumption, similar to the Chilean BT1 tariff.

3 THEORETICAL FRAMEWORK

3.1 Distribution networks

Distribution networks are composed of medium and low voltage networks, which present voltages ranging from 0.4 to 35 kV. Historically they have been the last link of the electricity supply chain that starts with generating power plants, normally located far away from consumption, followed by transmission networks, ending on distribution networks (sometimes there is a sub transmission network acting as an interface between transmission and distribution, giving an intermediate voltage step that helps the penetration to heavily populated cities or regions).

These networks typically start at a medium voltage substation which energizes several tree-shaped radial networks called distribution feeders, which interconnect themselves at medium voltage only under contingencies. This unmeshed design is a product of the minimization of the investment and operational costs under security and monetary constraints, apart from making fault detection and isolation easier and faster, which minimizes the probability of lack of supply, hence lower fine costs.

One important assumption is that the main capacity expansion driver is the client's consumption or demand. This assumption helps coining the concept of “fit and forget”, meaning that if you design a network to bear the toughest conditions of demand, it should also be sufficient for the rest of the operational conditions.

The return of the network investments is made possible given the tariffs constructed by the regulator agent. A common practice is to develop energized tariffs which charge

energy, transmission, power and distribution capacity as a function of energy consumption.

3.2 Impact of distributed power generation

For this section we will use the former definition of distributed generation, any power injection near consumers at the low voltage section of the distribution network, and present the theoretical impacts of the distributed generation that is discussed at the subject's literature.

Figure 3-1 presents an example of a distribution feeder with its voltage and power losses profiles without embedded generation. Voltage profiles are a function of voltage flowing through the branch and the electrical resistance of the same, while losses are a function of the squared current and the electrical resistance of the branch. When there is only consumption, the voltage profile, of the entire network, is a decreasing curve like the one shown in Figure 3-1.

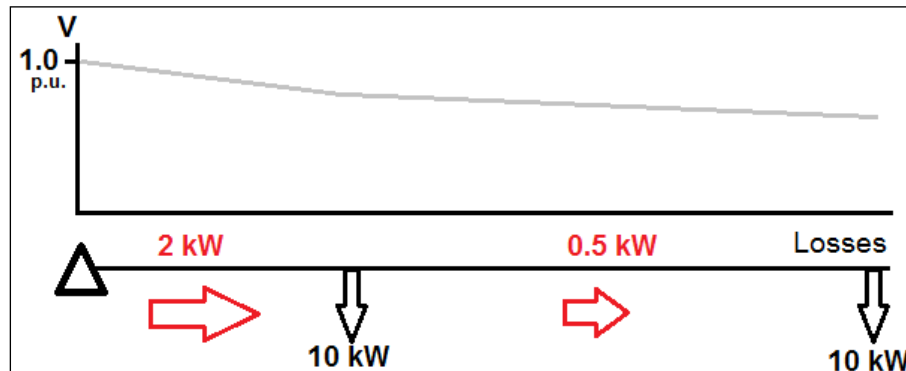


Figure 3-1: Feeder example without embedded generation

When a client injects small power close or at the same spot as the load, smaller meaning that it doesn't surpass the local load in magnitude, creates an impact in voltage, power losses and the networks thermal capacity use (Figure 3-2). This low penetration of embedded power injection decreases the voltage drop on every branch in which the currents are affected. Power losses also decrease.

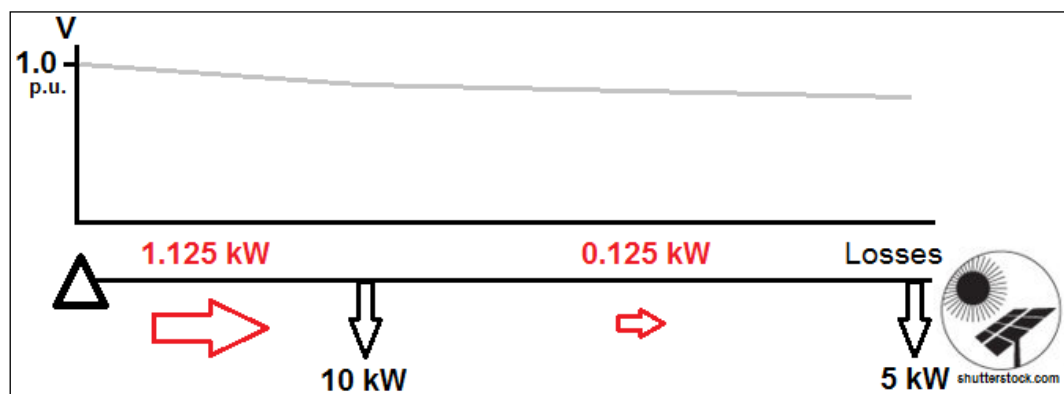


Figure 3-2: Feeder example with low embedded generation

When the amount of injected power produces a neutral or non-existent apparent consumption, as shown in Figure 3-3, the voltage drops and power losses keep decreasing, because of the lower currents flowing through the system. Technically speaking, the second branch of the feeder is dispensable and could be opened if the power injections and withdrawal are kept the same, but given the nature of the solar PV generation this equilibrium is not stable, hence the branch is not expendable.

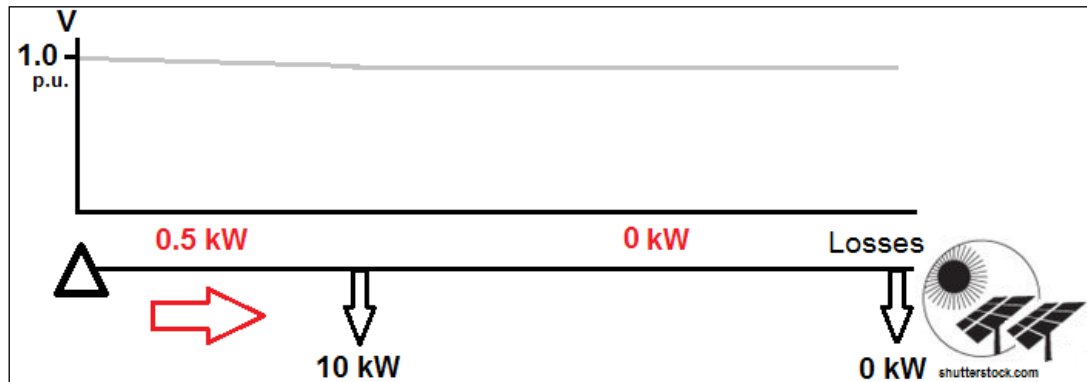


Figure 3-3: Feeder example with medium embedded generation

When higher penetrations occur, the current flows from the end of the tree-shaped feeder upstream, as shown in Figure 3-4, changing the typical voltage drop curves that exist in feeders with non-existing embedded generation, to a v-shaped curve, where the lowest voltage in the network is not the end of the feeder as before, but somewhere in the middle of the network. This point, apart from having the lowest voltage at the network, presents zero current.

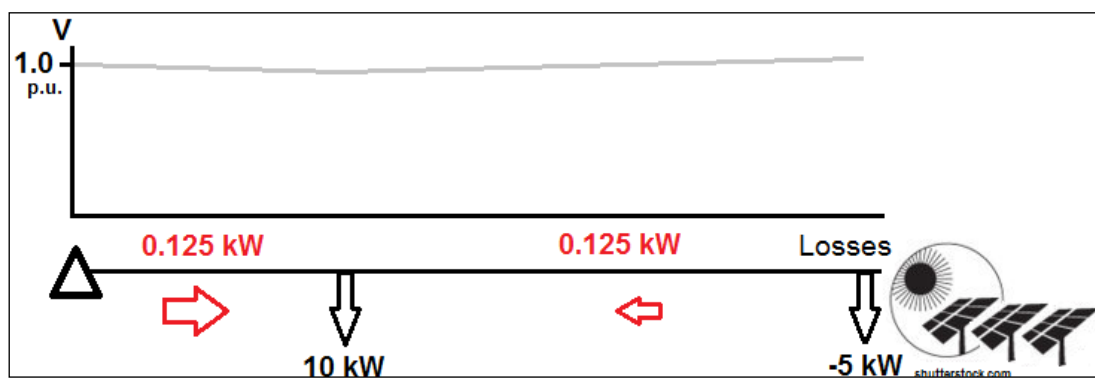


Figure 3-4: Feeder example with high embedded generation

Figure 3-5 presents a feeder with extreme embedded generation, satisfying the load only with the inner generation, having a zero apparent-consumption, when looked from the

feeder's header. These scenarios of penetration can present overvoltage problems given the fact that at distribution levels the voltage is controlled at the sub-station or feeder's header. From the point of view of power losses, this scenario presents higher losses than the high penetration scenarios, meaning that energy/power losses vs. DG penetration also present a v-shaped curve.

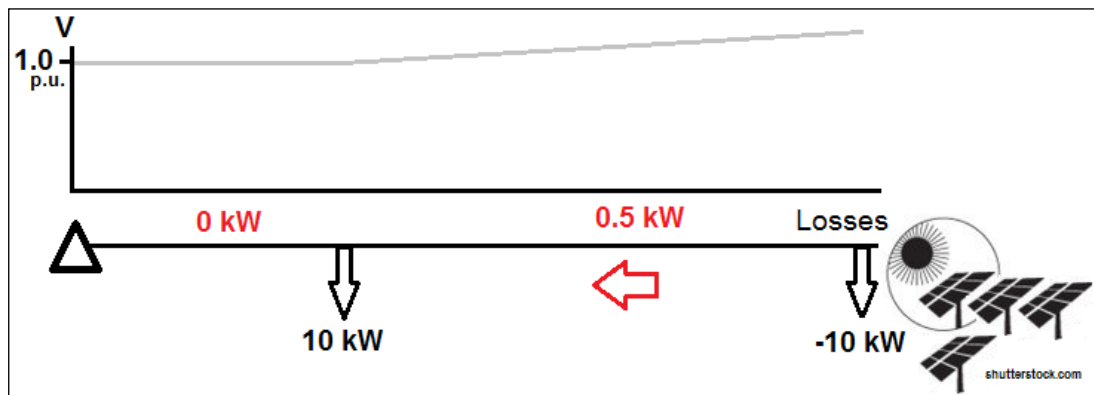


Figure 3-5: Example with neutral feeder with embedded generation

The overvoltage problems can be sharpened if the embedded power injections grow past the network-neutrality threshold in terms of the power that it needs at certain hours of the day. Figure 3-6, shows how the overvoltages and losses grow even larger, making the system unsafe, because the electric product doesn't meet the quality standards and is less efficient in terms of the energetic economy of the operation.

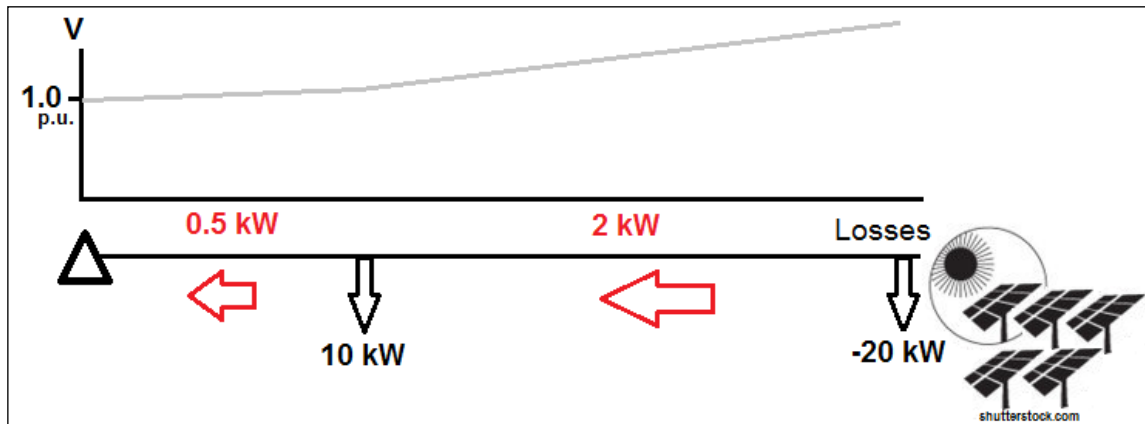


Figure 3-6: Example with exporting feeder with embedded generation

Figure 3-6 evidences that uncontrolled high penetrations of DG could trigger thermal capacity violations on branches that were designed only for load-induced stresses. In this case the branch that is transporting 2 kW of active power was originally designed to work under the stress that the transportation of 0.5 kW.

The example shown above explains the appearance of embedded generation in a simplified form. The reality holds much more complex and intricate distribution networks that can allocate almost any imaginable configuration of penetration of distributed power generation devices, creating as a result a large universe of scenarios that can happen in the nearby future. In order to simplify these possible scenarios analysis, two decisions were made for this thesis; the first one is to relate the power size or capacity of the generating device installed by a client with the design load magnitude of the same client, and the second is to create, under the first assumption, random penetration scenarios of DG and obtaining average results as a function of the amount of penetration achieved.

This proportion between installed capacity of generation and consumption is made with discrete intervals of 10 % per unit width, with 0.0-0.1 p.u. as the first interval and 2.4-2.5 p.u. as the last. This decomposition method for analyzing the penetrations scenarios helps understanding the phenomenon of solar PV penetration and its impact, adding a new way to regulate and limit the amount of embedded capacity of generation that can be installed in a network by making it a function of the consumption size of the same client. These sensitivity intervals will be called hereinafter behavior intervals.

3.3 Modeling of Distribution Networks

In distribution systems lines present higher resistance to reactance ratios than in transmission systems, implying that it is necessary to use an AC power flow formulation to have a more accurate representation of thermal capacity constraints and voltage profiles.

Lines are modeled using their short equivalent (Figure 3-7) using concentrated series parameters because of the spatial nature of distribution networks, where none of the branches is longer than 80 km (50 miles) [9], while transformers are modeled implicitly as the change in impedance and capacity constraints between the high and low voltage interfaces.

The mathematical AC power flow model is formulated as follows:

$$\text{Min } P \quad (1)$$

Subject to:

$$P_{ij} = g_{ij}V_i^2 - V_iV_j[g_{ij}\cos(\theta_{ij}) + b_{ij}\sin(\theta_{ij})] \quad \forall (i,j) \in \text{Branches} \quad (2)$$

$$Q_{ij} = -b_{ij}V_i^2 + V_iV_j[b_{ij}\cos(\theta_{ij}) - g_{ij}\sin(\theta_{ij})] \forall (i,j) \in \text{Branches} \quad (3)$$

$$v_{min} \leq v_i \leq v_{max} \quad \forall i \in \text{Buses} \quad (4)$$

$$\sum_{j=1}^N P_{ij} = G_{P_i} - D_{P_i} \quad \forall i \in \text{Buses} \quad (5)$$

$$\sum_{j=1}^N Q_{ij} = G_{Q_i} - D_{Q_i} \quad \forall i \in \text{Buses} \quad (6)$$

$$g_{ij} = \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2} \quad \forall (i,j) \in \text{Branches} \quad (7)$$

$$b_{ij} = -\frac{x_{ij}}{r_{ij}^2 + x_{ij}^2} \quad \forall (i,j) \in \text{Branches} \quad (8)$$

Where P_{ij} is the active power through branch ij , Q_{ij} the reactive power through the branch $i-j$, V_i the voltage on bus i , θ_{ij} the voltage angle difference between bus i and j , g_{ij} the conductance of the ij branch, b_{ij} susceptance of the $i-j$ branch, v_{min} and v_{max} are the lower and upper limit voltages respectively and P and Q the active and reactive power injected at the feeder's header. All parameters and variables are presented in their respective per unit basis.

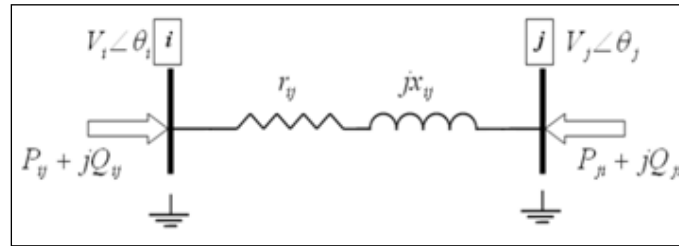


Figure 3-7: Short line model equivalent

3.4 Line Loss Compensation

Under normal conditions of operation transmission and distribution lines present, as stated before, voltage drops along their extension because of the resistance of the conductors and the current that flows through them. This voltage drops are a function of the line current of the circuit times the electric resistance of the conductors of the same. These drops in the voltage profiles have to be controlled in order to meet technical standards of electricity products. One way of controlling the voltage on distribution systems is to use power transformers that change their transformation ratio under load, giving the possibility to increase or decrease the voltage set point on the lower voltage side of the system (depending on the used control scheme). By setting a higher voltage set point at the distribution side of the transformer, the complete voltage profile of the feeder is raised, giving the possibility of meeting voltage standards without the use of reactive compensation at consumer level or changing the conductors for achieving a lower electric resistance of network.

This compensation needs a feedback of the voltage magnitude at certain buses of the network downstream, needing measurement devices to complete the feedback process.

4 METHODOLOGY

The proposed methodology consists in simulating the physical operation of a given distribution network under the penetration of DG, specifically PV, assuming present network conditions where virtually no storage capacity exists, low voltage state variable measurements are rare and practically non-existent, plus the fact that in a short time scale the only measures that DNO's can take against DG penetration are conductor and transformer upgrades (methodology of upgrade will be later on discussed). After the physical operation, an economic model simulates the economic operation under a given tariff scheme. This proposed methodology of an operational model followed by an economic model is used by de Joode et al. (2010) [6]. The proposed methodology presents the following differences which are the main contributions. A parameterized behavior of clients (which will be later on discussed) is proposed in order to give a base for the creation of random penetration scenarios, based on the economic logic that larger clients would normally install a larger amount of PV DG. The proposed methodology also ensures that thermal capacities are met throughout the network by upgrading the series elements (conductors and transformers) that overpass their thermal operational threshold. This capacity related costs help in the process of giving complete signals of the economic impact of DG on the distribution networks.

An operational summary is proposed in order to decrease the volume of data that the operational model produces as its output, simplifying the economic model stage. This methodology let us understand the technical and economic impacts of the penetration of

PV in real size distribution feeders. Figure 4-8 shows the information flow diagram between the two models and their respective parametric inputs.

The amount of possible DG penetration scenarios is large enough to make the computation off them unfeasible in terms of computational time, which is why the proposed methodology generates a lower number of random penetration scenarios in order to have an expected value analysis of the DG penetrations effect. This process is repeated for every behavior interval that is analyzed.

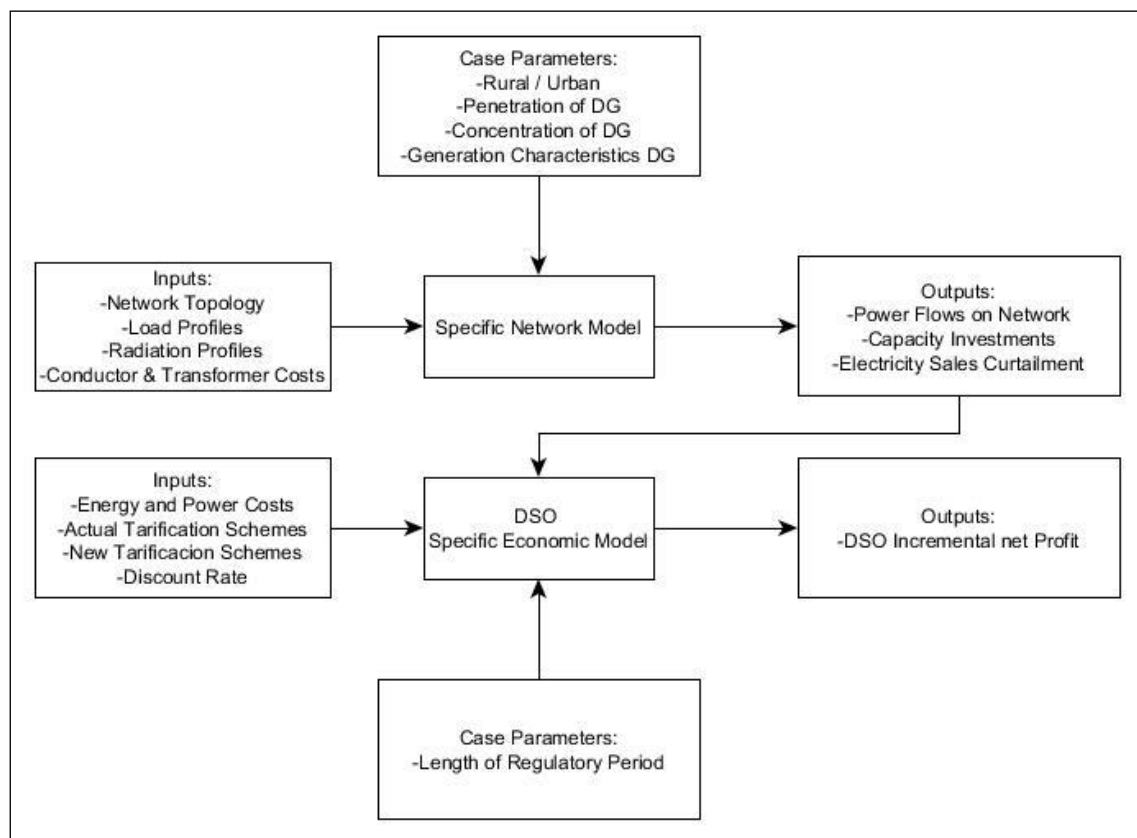


Figure 4-8: Dual model flow diagram

4.1 The Model

This section discusses the proposed the operational and economic model.

4.1.1 Operational model

As Figure 4-8 shows, the operational model inputs are load and generation profiles of the analyzed network, network topology, conductors and transformers upgrading costs and voltage restrictions. This data is loaded into a balanced AC power flow model, programmed using AMPL [1] based on Tapia et al. [2] and Vanderbei's AC power flow codes [3] and executed at the NEOS server [4], to extensively solve AC power flows to represent a study horizon operation of a feeder for randomly created scenarios of PV DG penetration. After every converged power flow thermal capacities are checked, calculating the capital expenditure as the cost of changing lines and transformer to meet thermal capacities throughout the network for each scenario. After every thermal capacity violation is solved the model recalculates the specific configuration that triggered the thermal restrictions. If no new conductor technology or transformer can solve the thermal capacity violations the penetration scenario is dropped and another one is started right away. The details of the series element upgrade are later on discussed.

Given the uncertainty of the location and size of the DG penetration, the model generates random penetration scenarios of solar DG with a previously assumed behavior of the customers that install solar power. This is made by defining minimum and maximum limits of installable solar power relative to the size of the client. E.g. if the behavior interval is 0.0 and 0.1 p.u. relative to the clients consumption size, a customer with a 5 kW could install from 0 to 0.5 kW of solar PV power. This logic of relating the

generation size with the consumption size adds a dimension for the sensitivity analysis that can be carried out ex-post, giving different regulatory signals on how to limit DG power installation on the costumer side of the grid, allowing conservative DG programs to be executed, decreasing the unpredictable side effects of its appearance.

The flow diagram of the random penetration methodology scenario is shown in Figure 4-9.

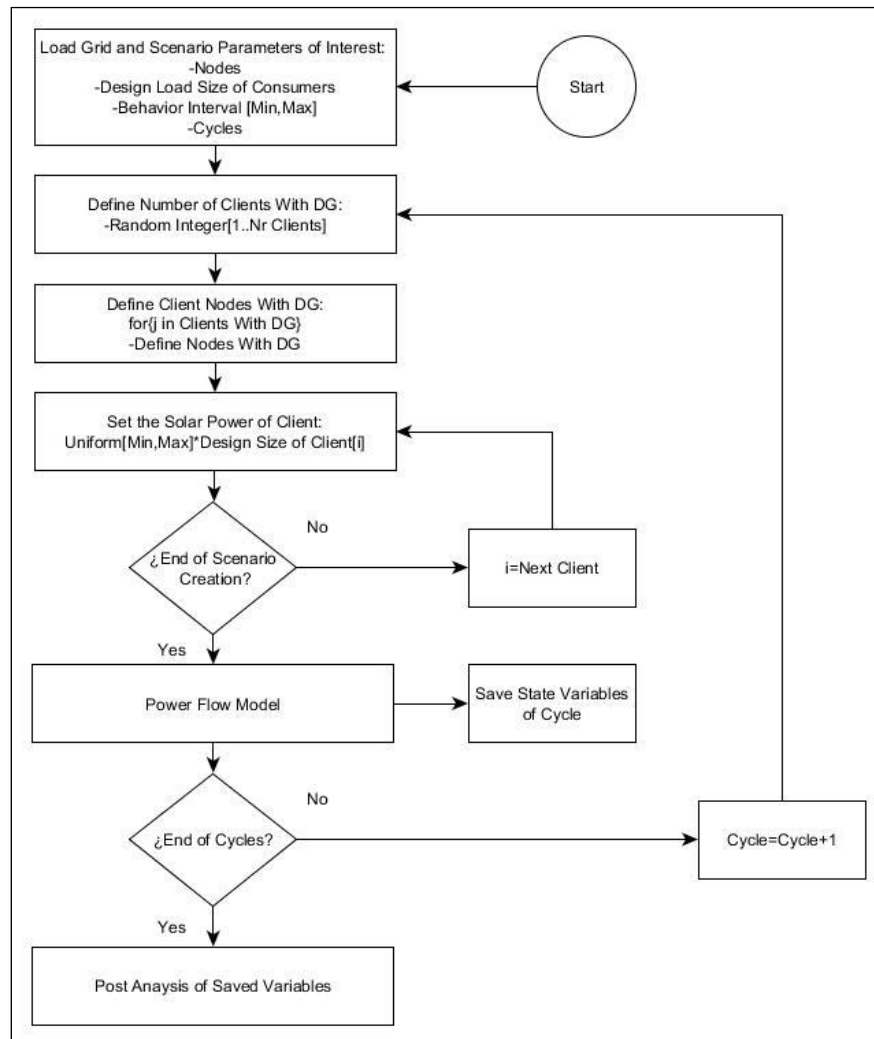


Figure 4-9: Random DG penetration builder flow diagram

In case the power flow calculation does not converge, the penetration scenario is dropped, due to its technical unfeasibility, and another one is started right away. This non-convergence can only be explained by voltages higher or lower than those allowed by the voltage constraints loaded to the model.

The flowchart of the proposed model is shown in Figure 4-10:

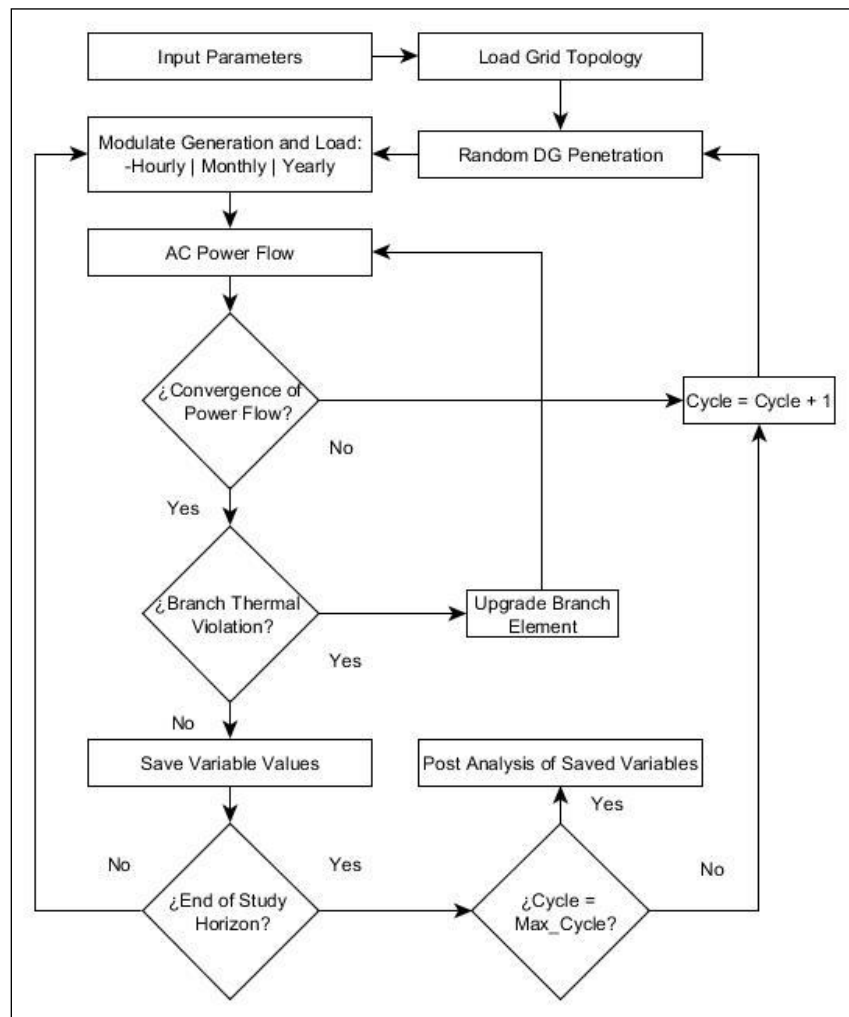


Figure 4-10: Flow chart of the operational model

4.1.1.3 Network topology

The model allows any kind of distribution network topology to be loaded.

4.1.1.4 Conductors and Transformers Upgrade

4.1.1.4.1 Conductors

In order to capture the capacity related costs of DG in terms of conductor replacement, a technical and economical criterion was used to minimize the cost of investment plus present cost of Joule effect losses. This method calculates the net present cost per kilometer of a variety of conductors, working under a constant current for a given period of time. The net present cost equation for a given conductor “ k ” is stated as follows:

$$NPC_k = i.c._k + \sum_{t=1}^T \left[\frac{8760I^2 R_k P_E}{(1+r)^t} + \frac{12I^2 R_k P_P}{(1+r)^t} \right] \quad (9)$$

Where $i.c._k$ is the investment cost of conductor “ k ” per km [US\$], T the number of years of the economic evaluation, R_k the electric resistance per km of conductor “ k ” in [Ohm/km], I the operation current [A], P_E the energy cost in [US\$/Wh], P_P the monthly cost of power in [US\$/Watt/Month] and r the annual discount rate.

This process is repeated for a discrete set of currents $[0 \dots I_{\max}]$, where I_{\max} is equal to the highest ampacity rated conductor. All these present values, when charted together, are used to create a lower envelope cost of investment and operation curve as a function of current (Figure 4-11). This envelope also shows the optimal current intervals of operation for every analyzed conductor. As Figure 4-11 shows, this lower envelope curve lets us graphically understand the economic order of merit of the different

candidate conductors for the upgrades. Efficient conductors are present at the lower envelope, while non-efficient ones are not present. Figure 3-1 presents the efficient conductors (1, 2 and 4) and the inefficient ones (3).

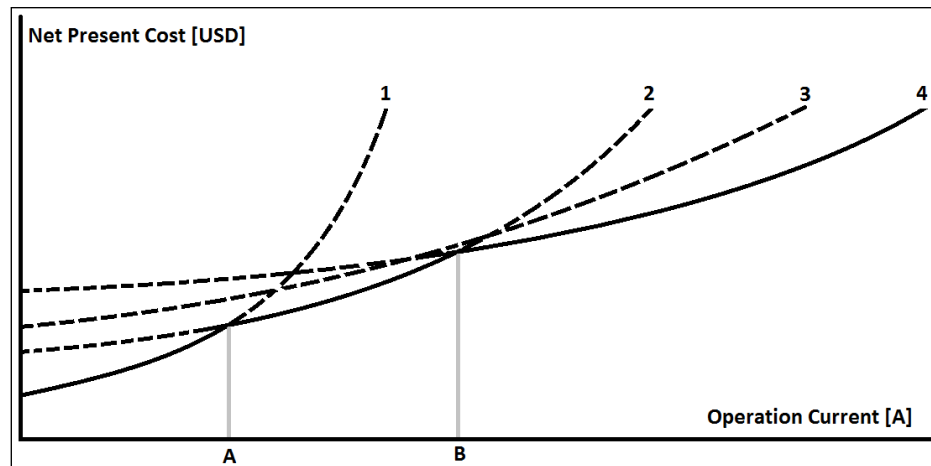


Figure 4-11: Efficient conductor change lower envelope

The same set of conductors used for the last Distribution Aggregated Value Study (2012) was applied for this model. Different sets of efficient conductor were made, depending on the voltage level (medium or low) and the type of channeling (aerial or underground). The costs of the conductors for the different sets are shown in .

4.1.1.4.2 Transformers

In the case of the transformers, a set of 8 candidates with increasing capacity was developed, ranging from 15 kVA to 1 MVA. This ensures capacity upgrade selection for extreme penetration scenarios and better resolution of cost of capacity upgrades (Table 4-5).

Table 4-5: Distribution transformer costs

Capacity [MVA]	Cost [MUS\$]
0.015	3.4
0.030	4.0
0.045	4.8
0.075	6.4
0.150	9.4
0.300	12.9
0.500	15.0
1.000	35.5

4.1.1.5 Assumptions

In order to simplify the operational model the following assumptions were made:

- Equal load profile for every client on the network
- Three phased balanced system
- No reactive compensation for the network's design
- Feeder header transformer continuous tap changer $\pm 5 \%$

4.1.1.6 Operation summary

In order to record the complete study horizon a cumulative process of saving the interest variables is proposed, which stores the net present value of energy and power discounted a given rate. This method let us sum up the study horizon of each penetration scenario into nine parameters, reducing the volume of data that is present at the interface of the operational model and the economic model. Figure 4-12 shows the process of operation summary at the client side. After each converged power flow, the model stores the net present value of consumption and generation with the showed division. The same process is done for the amount of energy that is bought and sold (imported and exported)

at the feeders. Finally the net present value of power that is bought at the feeder's header and sold to clients is also stored. This allows obtaining the desired cash flows by multiplying the operation building blocks by the cost of the element. These summary parameters will be called hereinafter operational building blocks.

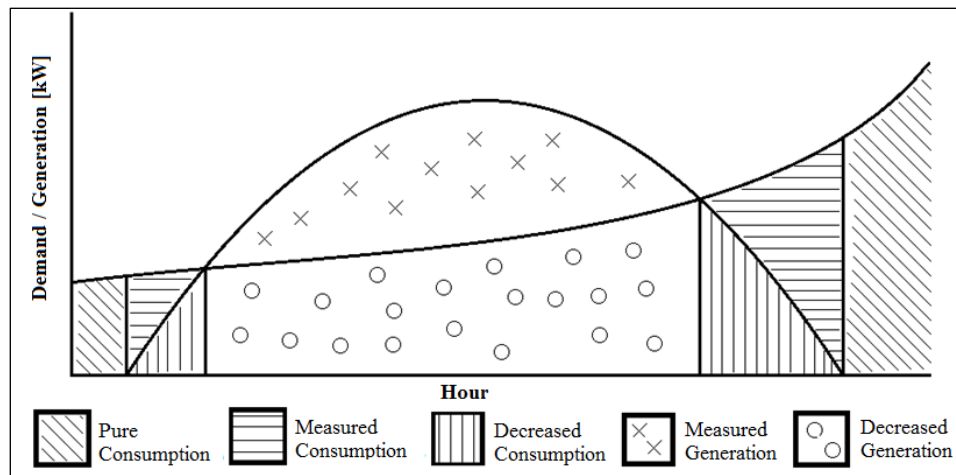


Figure 4-12: Demand generation curve segmentation

List of operational building blocks:

- 1) Net Present Pure Consumption
- 2) Net Present Measured Consumption
- 3) Net Present Decreased Consumption
- 4) Net Present Measured Consumption
- 5) Net Present Decreased Consumption
- 6) Net Present Headers Energy Purchase
- 7) Net Present Headers Energy Selling
- 8) Net Present Clients Power Purchase
- 9) Net Present DNO Power Purchase

4.1.2 Economic model

The economic model takes into account the revenues and costs of the operational exercise for the defined study horizon. This is done for each feasible penetration scenario that the operational model analyzes. Revenues and costs are calculated using the summary variables calculated with the operational model.

4.1.2.1 Revenues

The considered revenues for this exercise are tariffs paid by clients for their electric consumption for a given set of tariffs, which can range from fully energized (volumetric) tariffs to fix power and network use charges. In addition, the surplus energy exported back to the transmission network upstream (exporting of energy) will be considered a positive cash flow for the DNO.

This assumption is based on the fact that these reverse power flows will be used in other feeders of the same upstream sub-station or even travel through the sub-transmission system into another sub-station owned by the same DNO.

4.1.2.1.1 Tariffs

Tariffs are the instrument by which the DNO's recover their operational costs and investments. The economic model allows any tariff that can be constructed with the use of the operational building blocks to be analyzed. E.g. if a client is regulated using a fully energized tariff, the DNO will perceive positive cash flows only for the measured consumption. Figure 4-13 represents the case of a client that has an energized tariff and also installed a power generation device. The DNO will only be able to charge for the

measured consumption (green area) and given the distributed generation regulation the client will be remunerated for the injected energy back to the grid (red area).

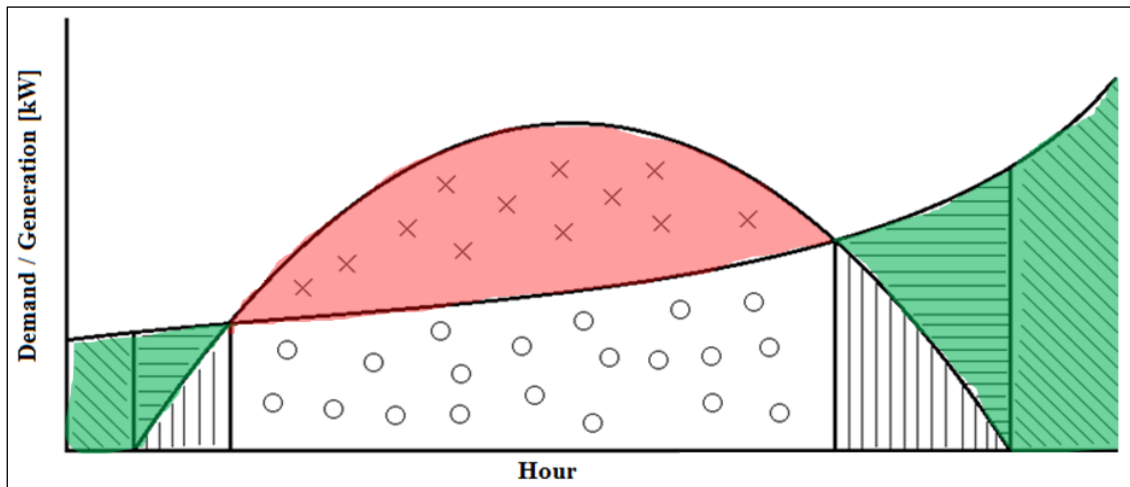


Figure 4-13: Fully energized tariff revenues and costs

The operational building blocks allow the modeling of non-volumetric tariff which charge capacity and network costs in a monthly and fixed basis.

4.1.2.2 Costs

The operational costs incurred by the distribution company are the energy and power purchase from the transmission network at the feeder's header and the energy paid to the distributed energy owners depending on the analyzed tariff scheme.

4.2 Study Case

Two representative types of distribution networks were analyzed: urban and rural. The first one presents shorter branches and high density of consumers, while the second one presents longer branches and low density of consumers. The feeders used for this paper were taken from the last distribution aggregated value study for Chilectra (2012), the

Santiago distribution company, which is done every four years as a tariff exercise to evaluate the cost of an efficient yardstick company giving service to different distribution areas. These two network examples help understanding the process of solar DG penetration.

4.2.1 Urban

The analyzed urban feeder (Figure 4-14) consists of 4.67 km of 12 kV three-phased lines, 4.25 km of three-phased 380 V lines and 156 clients that produce a peak load of 5.54 MVA at the 4th year of operation.

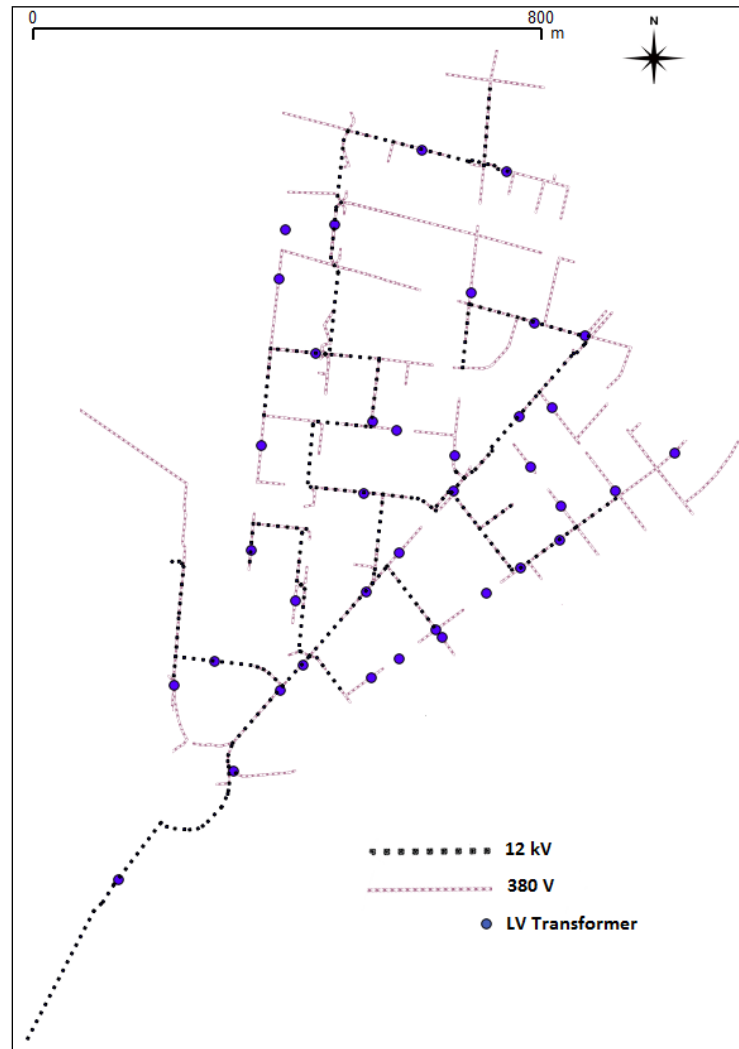


Figure 4-14: Urban distribution feeder (Vitacura)

4.2.2 Rural

The analyzed rural feeder consists of 69.43 km of 12 kV three-phased lines, 83.572 km of three-phased 380 V lines and 546 clients that produce a peak load of 1 MVA at the 4th year of operation (Figure 4-15).

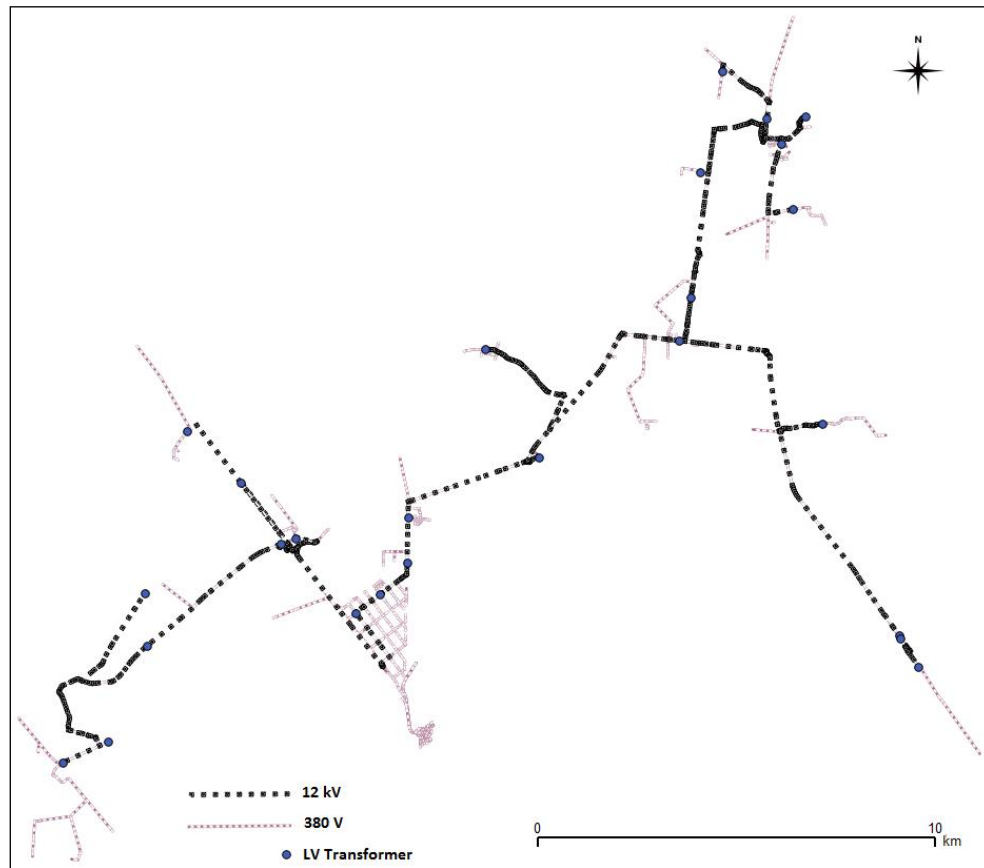


Figure 4-15: Rural distribution feeder (Batuco)

4.2.3 Economic parameters

The energy price used is 104.36 US\$/MWh and capacity 8.24 US\$/kW/Month, while the energized capacity charge is 21.4 US\$/MWh. Network charges are 22.9 US\$/MWh and 7.5 US\$/kW/Month for the energized and fix tariffs respectively. The exchange rate used for the dollar is 550 CLP/US\$.

4.2.4 Regulation

Two existing regulated tariffs were used for the income calculation, the BT1 and BT2 tariffs (details of their components in annex 1 and 2). Additionally a new tariff was presented with the purpose of regulation signals, the BT1 buy all sell all. This new tariff

is essentially the BT1 tariff with the exception that the client is separated in two entities, a consumer and a generator. The consumer pays for his entire BT1 bill as usual, while the generator receives money for every kWh injected to the network at normal energy price plus the average avoided losses priced at the same value [10]. This new tariff will be called BT1*.

The Chilean regulation recognizes the power that distributed generators inject back to the grid and gives a certain monetary value to it. This value is the same as the cost at which consumers buy energy from the DNO's, plus the avoided energy losses that did not occur.

Distributed generators have to pay for all the upgrades that have to be done to the grid as a consequence of the connection to the network, avoiding a. These costs include conductor and transformer upgrades. In other words this is deep connection charges scheme with no use of system charges, apart from the ones paid as consumers.

4.2.5 Demand and generation

A database of one thousand regulated consumers of Chilectra, the biggest distribution system operator in Chile, was used to create the hourly profile of the consumers. This database has hourly resolution measurements that match the resolution of the radiations database (Figure 4-16).

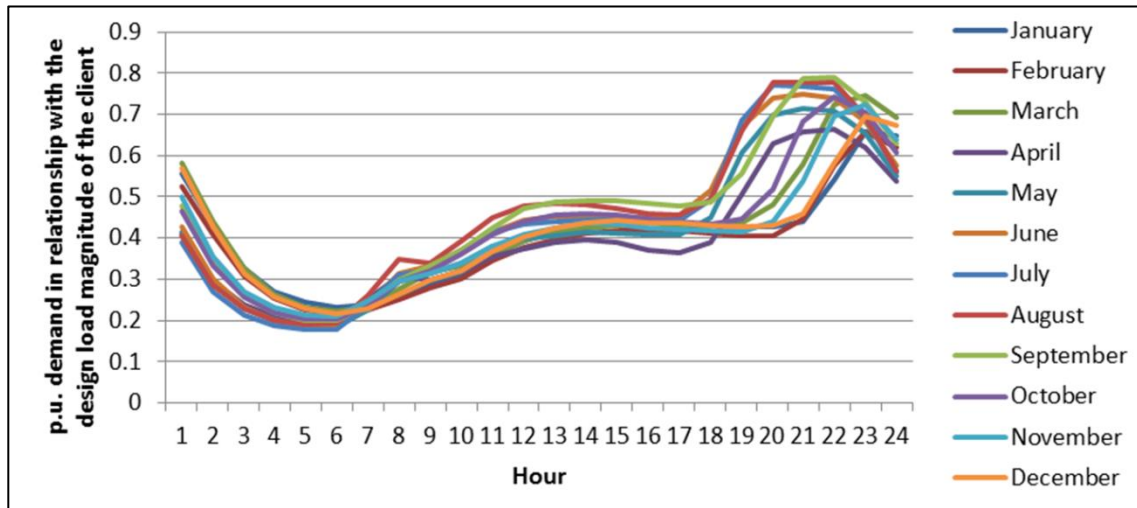


Figure 4-16: Hourly average consumption profile of 1,000 regulated clients of Chilectra

A study of Chilean solar radiation [8] by the Universidad Técnica Federico Santa Maria was used to create an hourly profile of the per unit generation curved used for the area of study (Figure 4-17). These profiles assume that the panels have a 0° inclination towards north.

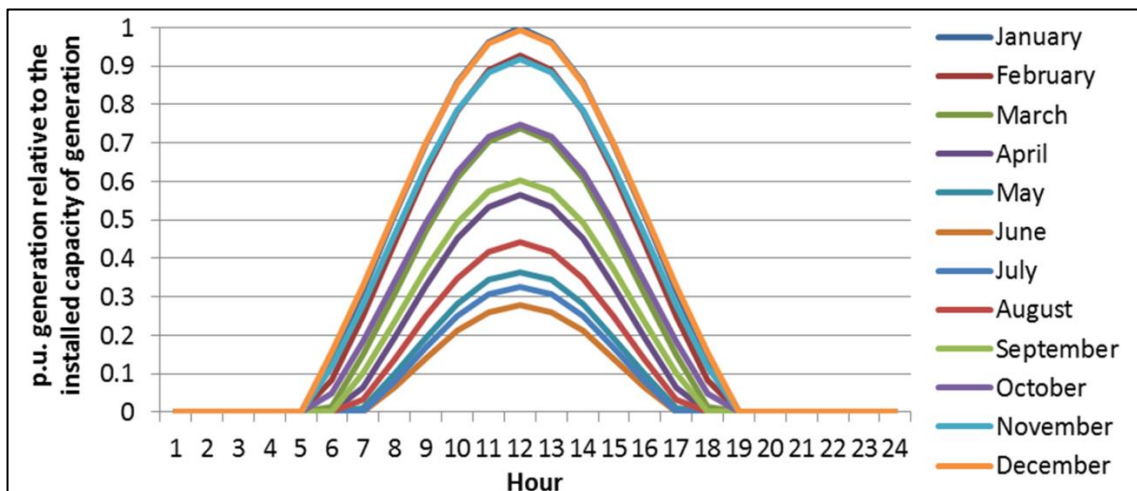


Figure 4-17: Hourly p.u. PV generation profiles of a panel at 0° of inclination

4.2.6 Technical standards

Chilean General Electric Services Regulation, which are ± 6 % p.u. for medium voltage systems (12 kV) and ± 7.5 % p.u. for lower voltage systems [7].

5 RESULTS

In this section electrical, capacity and operational results are shown and discussed in order to provide clarity for future regulation of distribution with embedded generation. Each results section is subdivided in study cases accompanied with their respective tap changer analysis. For both rural and urban study cases, the percentage of penetration will be calculated as the ratio between the installed MW of solar power and the maximum design demand of the feeder for the 4th year of operation in MVA and as stated before, the DG clients behavior of power installation will be divided in per unit basis intervals related to the load size of the clients.

5.1 Electric Results

The decrease in consumption, or even the power injection back to the network, impacts the network at variables such as voltage, losses and power flows, which by doing the aftermath, affects the operational outcome of the companies through the tariffs, acting the latter as an interface of the real electric operation variables and the economic operation with its own separate set of variables. This section analyzes the electric variables and how the penetration of distributed generation affects them.

5.1.1 Voltage Impact

Voltage magnitude is the most tangible characteristic of the electricity product for every user of the network; it dictates how electric devices would work when plugged to the network, for good and bad. When low, devices would work in strange ways or not work

at all and when high, devices could get burned if no protection elements are part of their electronic design.

Voltages let us understand how the quality of the product changes throughout the network, being good for the client as long as it stays in the allowed band defined by the technical regulation. On the other side, the lower the voltage, the higher the power losses that the network has, because of the tradeoff between current and voltage (assuming a constant power load model), so distributors have the incentive to raise the voltage profile of the feeder in order to minimize losses but being careful on not producing overvoltages on certain nodes of the network. These voltage rises can be achieved with a higher tap changer set point and/or with reactive compensation, using capacitors located near the low voltage zone, if spatial constraints allow it.

5.1.1.1 Voltage Profiles

This section presents the DG impact on the distribution voltage profiles under different penetration scenarios.

In order to have a fair comparison of the voltage profiles between the different penetration scenarios a fixed set of nodes with clients was selected for both the urban and rural cases. This set was kept fixed for all penetrations scenarios and the only changed parameter was the amount of DG that they install relative to their load size (behavior interval).

5.1.1.1.1 Urban

Twelve urban feeder client nodes were selected to allocate PV power. These nodes were kept fixed in order to do a *ceteris paribus* comparison for the different penetration scenarios. Figure 5-18 presents the voltage profile of the urban feeder without tap changer at the first year of the analysis horizon, month January at noon. The nodes with generation, and the ones near it, see their voltage profile dramatically changed for different penetration percentages.

This node configuration doesn't allow more than a 4 p.u. behavior interval because of the overvoltages that it produces locally in some portions of the network.

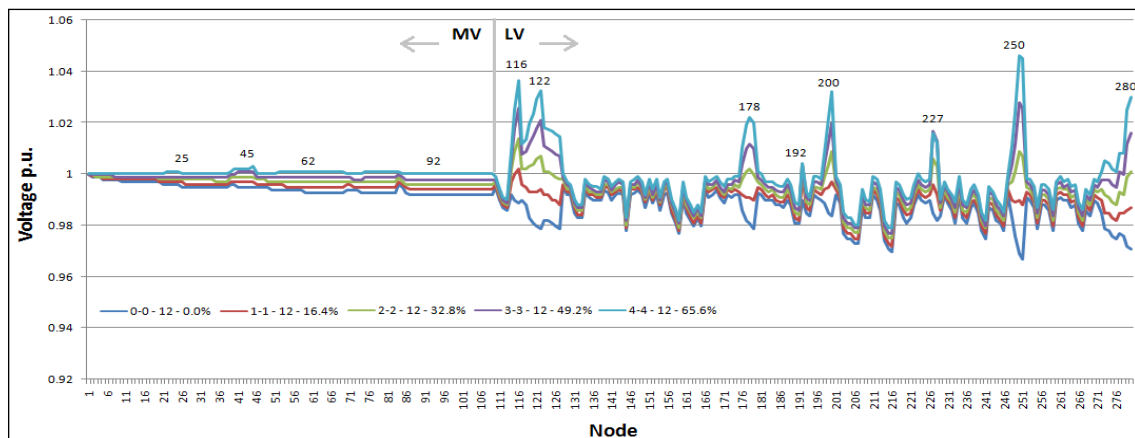


Figure 5-18: Urban feeder without tap changer voltage profile

When a tap changer is used (assuming a perfect voltage measurement system), larger penetrations of DG are achievable. A lower set point at the feeder's header is needed to decrease the entire voltage profile of the network, allowing higher relative voltages to be achieved on certain nodes in comparison with others (Figure 5-19).

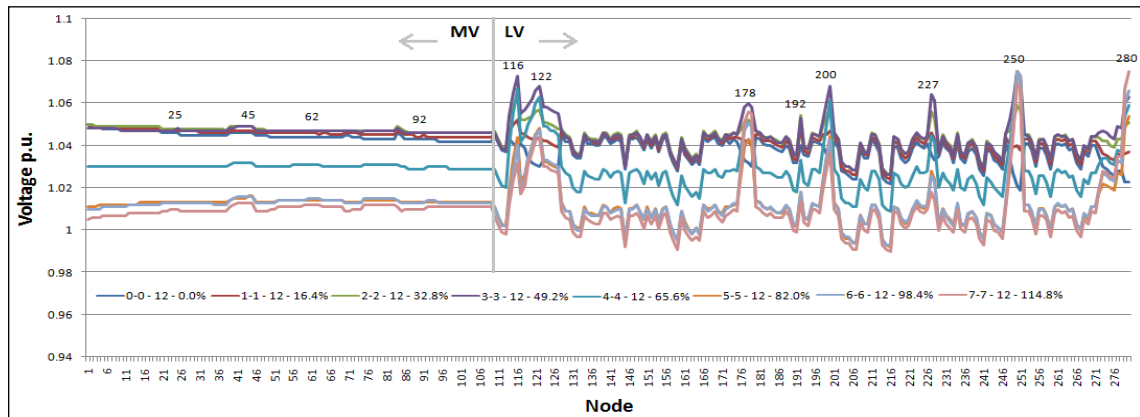


Figure 5-19: Urban feeder with tap changer voltage profiles

5.1.1.1.2 Rural

For the rural feeder case 15 nodes were selected for doing a *ceteris paribus* comparison. Only a 38.4 % of penetration was achieved before presenting overvoltages that leads to an electric product out of the accepted quality standard range. Figure 5-20 shows how again the nodes close to the generation had their voltages magnitude raised because of the presence of generation nearby. These higher voltage profiles diminish power losses at the network but increase the chance of overvoltages if no penetration control is implemented. Figure 5-20 also shows how the voltage of a node that presents active power injection can shift so dramatically. Node 1.050 presents the biggest voltage difference relative to the base case, almost coming out of the ± 7 p.u. allowed voltage band.

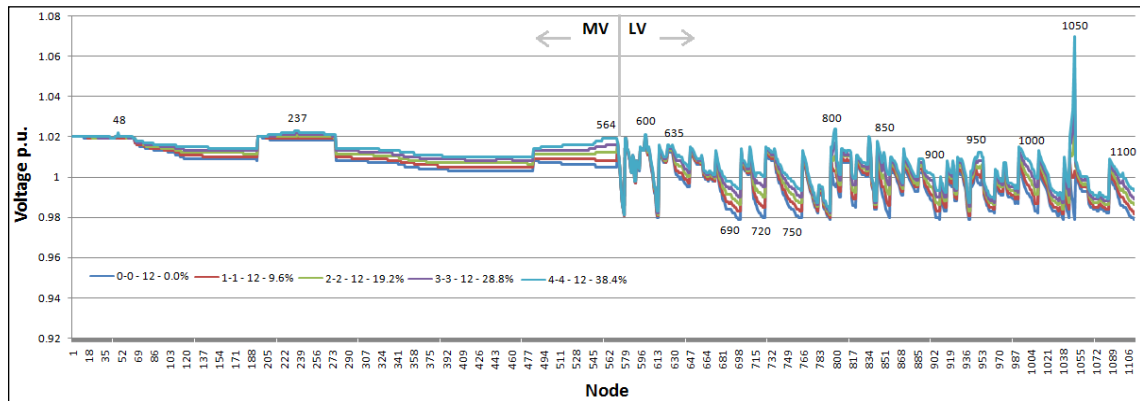


Figure 5-20: Rural feeder without tap changer voltage profiles

Figure 5-21 presents the results for the rural feeder with tap changer. This case allows higher penetrations to be feasible because of the lower voltage set points at the feeder's header that lowers the entire voltage profile of the feeder. The rural feeder, for this exercise, allows less penetration than the urban feeder (114 % vs. 57.6 %).

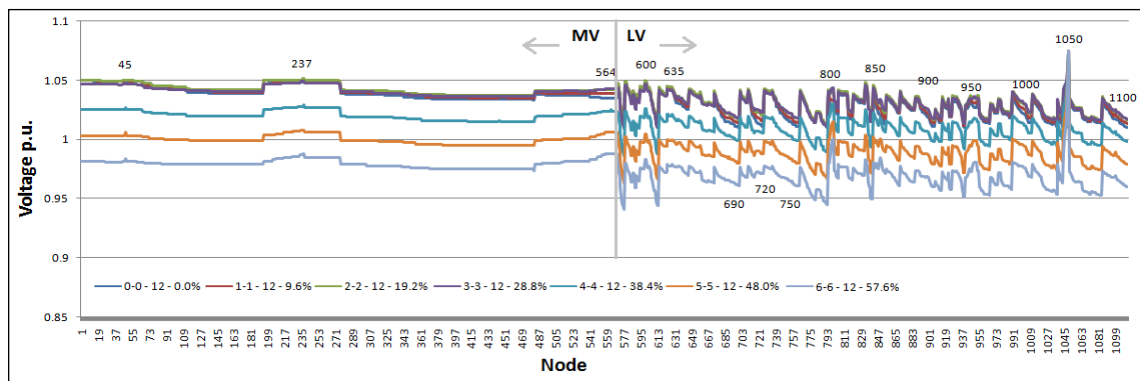


Figure 5-21: Rural feeder with tap changer voltage profiles

5.1.1.2 Voltage Violations

Not all power flow configuration scenarios converge, and under the current formulation of the AC power flow it means that the some of the node voltages are under or over the

allowed limits. This sections analyses the rate of overvoltages for the different penetration scenarios and behavior interval of clients

5.1.1.2.1 Urban

5.1.1.2.1.1 No Tap Changer

The values shown in Figure 5-51, Figure 5-52 and Figure 5-53 are results of scenarios where the AC power flow converged. Given the construction of the model, the only way that a power flow can't converge is by having under or overvoltages at any bar of the system. This second issue, overvoltages, is the main concern that could limit the penetration of distributed generation and give strong regulative signals, apart from the economic signals. Figure 5-22 shows the probability of non-convergence for discrete penetration intervals.

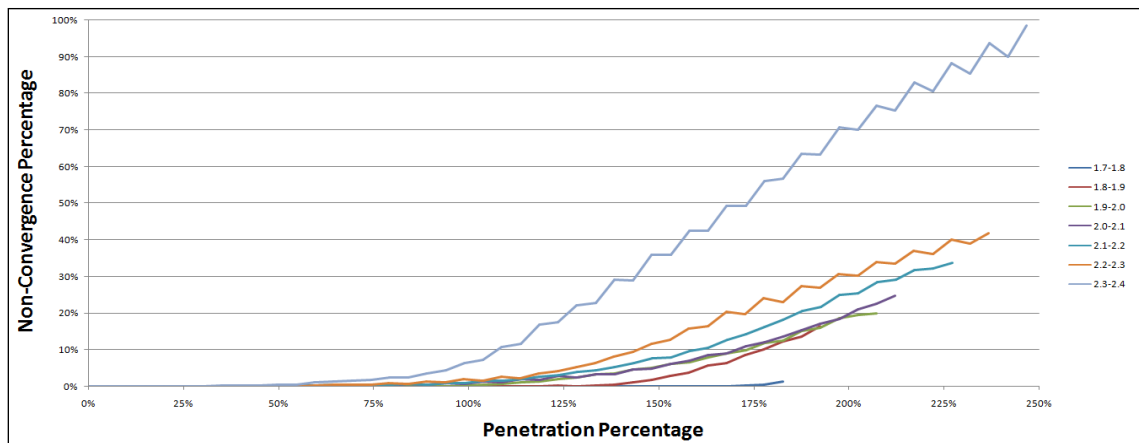


Figure 5-22: Non-Convergence probability of solar DG penetration for the given behavior scenarios for the urban case without tap changer

Every behavior interval lower than 1.7-1.8 p.u. has 100 % convergence for any penetration scenario, hence no overvoltages are detected in this cases. After the 1.7-1.8

p.u. interval the minimum penetration for non-convergence starts to decrease achieving a minimum value of 34.8 % of penetration for the upper 2.3-2.4 p.u. interval of behavior. Table 5-6 shows the minimum penetration percentage for each behavior interval that activates voltage restrictions.

Table 5-6: Minimum non-convergence penetration for the different behavior intervals

Behavior interval [p.u.]	Urban Feeder Minimum Penetration percentage of Non-Convergence
1.7-1.8	167%
1.8-1.9	123%
1.9-2.0	93%
2.0-2.1	59%
2.1-2.2	54%
2.2-2.3	50%
2.3-2.4	34%

5.1.1.2.1.2 With Tap Changer

The urban tap changer case does not present non-convergence for the analyzed penetration scenarios (10.000 random penetration scenarios from the behavior interval 1.4-1.5 till the 2.3-2.4).

5.1.1.2.2 Rural

5.1.1.2.2.1 No Tap Changer

Just as the urban case, overvoltages occur. Figure 5-23 shows the overvoltage frequency for every behavior interval that was analyzed, as a function of the penetration value.

The rural feeder presents a higher voltage sensitivity to power injection in its nodes in comparison with the urban feeder. Firstly the minimum behavior scenario that presents

overvoltages is 1.5-1.6 (the urban case first non-convergence scenario was the 1.7-1.8 behavior interval). Secondly the penetration % needed to trigger non-convergences is less than in the urban case. This is all explained by the high resistance of the feeder due to the big areas that it has to supply with electric energy. Any power injection far from the feeder's header would have as a consequence a voltage rise near the generation sites, because of the decreasing current that has to travel from the feeder's header to the power injection point. If this current inverts its direction the probability of having an overvoltage rises.

Table 5-7 shows the minimum penetration percentage needed to trigger overvoltages on the rural distribution feeder.

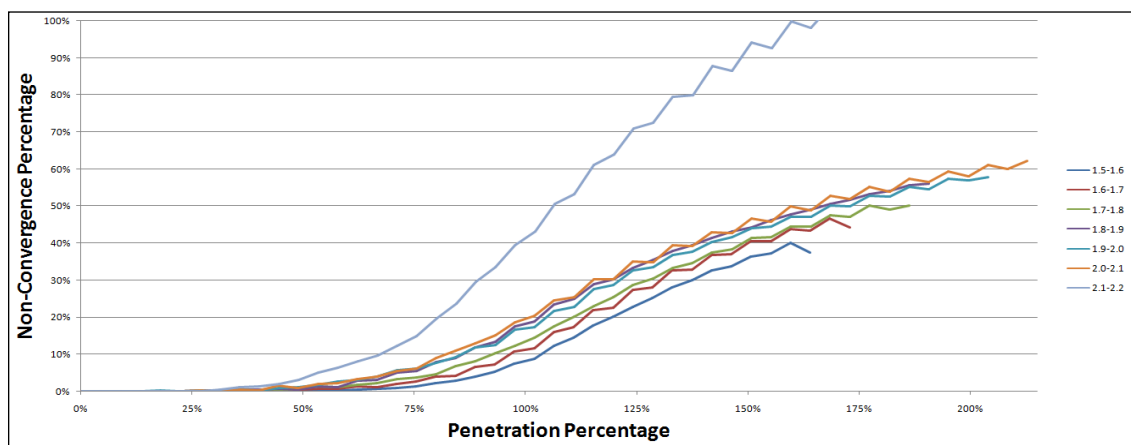


Figure 5-23: Non-convergence probability of solar DG penetration for the given behavior scenarios for the rural feeder without tap changer

Table 5-7: Minimum no convergence penetration of the behavior intervals

Behavior interval [p.u.]	Rural Feeder Minimum Penetration percentage of Non-Convergence
1.2-1.3	119%
1.3-1.4	71%
1.4-1.5	53%
1.5-1.6	36%
1.6-1.7	35%
1.7-1.8	31%
1.8-1.9	27%
1.9-2.0	18%
2.0-2.1	16%
2.1-2.2	10%

When the minimum non convergence penetration percentage of the urban and rural cases is compared, it is clear that urban feeders are naturally prepared for keeping the voltages in the accepted tolerance band while rural feeders aren't (assuming that no active voltage control schemes are implemented). On the other hand, urban feeders are well prepared for operating under higher nominal currents given their oversized design, while urban feeders are not. These two concepts give us the following hints. Firstly, if overvoltage problems in rural feeders are solved clients could allocate a large amount of DG relative to their load size and secondly, urban feeders have less overvoltages problems in comparison with rural feeders, leaving the capacity problem as the bottleneck for the DG.

Table 5-8 shows the comparison:

Table 5-8: Minimum non convergence penetration for the behavior intervals

Behavior interval [p.u.]	Rural Feeder Minimum Penetration percentage of Non-Convergence	Urban Feeder Minimum Penetration percentage of Non-Convergence
1.2-1.3	119%	-
1.3-1.4	71%	-
1.4-1.5	53%	-
1.5-1.6	36%	-
1.6-1.7	35%	-
1.7-1.8	31%	167%
1.8-1.9	27%	123%
1.9-2.0	18%	93%
2.0-2.1	16%	59%
2.1-2.2	10%	54%
2.2-2.3	-	50%
2.3-2.4	-	34%

5.1.1.2.2.2 With Tap Changer

Overvoltages occur only for high penetration, over 200 %, and behavior interval scenarios, 2.2-2.3 and 2.3-2.4. This means that high penetrations can be achieved without causing overvoltages when measuring devices are used. Figure 6-24 presents the non-convergence probability curve for the different behavior intervals that present overvoltages.

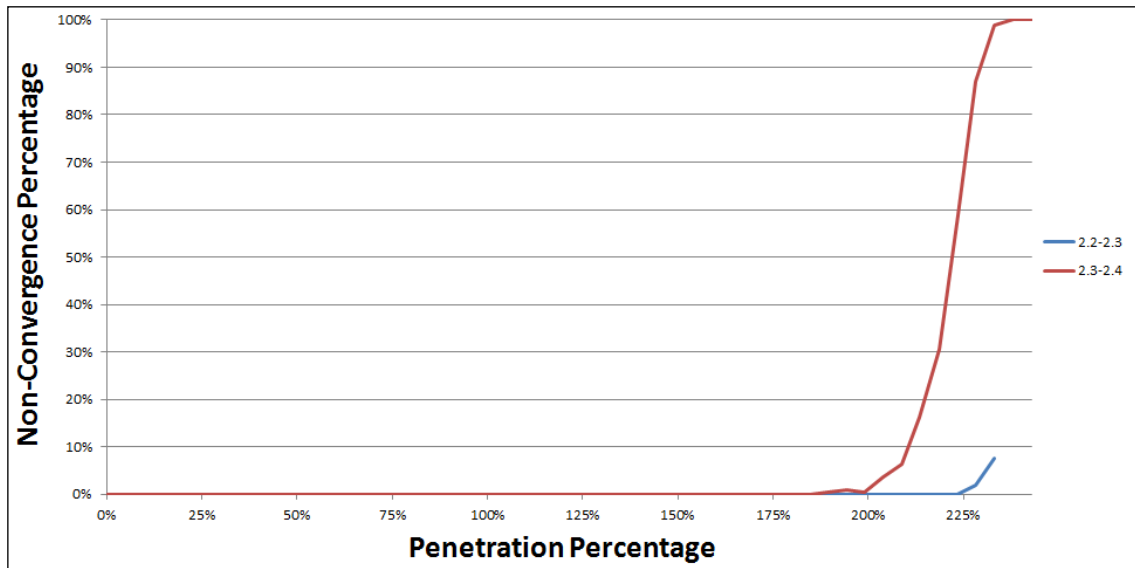


Figure 6-24: Non-Convergence percentage of solar DG penetration for the given behavior scenarios for the rural feeder with tap changer

Table 6-9: Minimum non-convergence penetration of the behavior intervals

Behavior interval [p.u.]	Rural Feeder Minimum Penetration percentage of Non-Convergence
2.2-2.3	225%
2.3-2.4	188%

5.1.2 Energy Losses

The penetration of DG produces a decrease of operational losses by cutting the distances that the currents have to travel in order to meet the demand needs. Over a certain penetration value, and for certain hours of the day, the generated power surpasses the load, having as a result an export of the surplus generated power back to the feeders header and upstream, to the high voltage transmission system. This kind of operation achieves the same or even higher level of power losses than the base case, producing, in some scenarios, higher operational costs.

The index used to reflect the operational energy losses is the net present energy losses value shown in equation 10:

$$Net\ Present\ Losses\ Value = \sum_{t=1}^4 \frac{Annual\ Energy\ Losses}{(1 + r)^t} \quad (10)$$

The use of this index comes practical when net present costs want to calculated. It only takes the calculation of the Net Present Energy Losses times the cost of energy purchase value.

5.1.2.1 Urban

5.1.2.1.1 No Tap Changer

Figure 5-25 presents the Net Present Losses Value for the urban feeder without tap changer for the different penetration scenarios and behavior intervals.

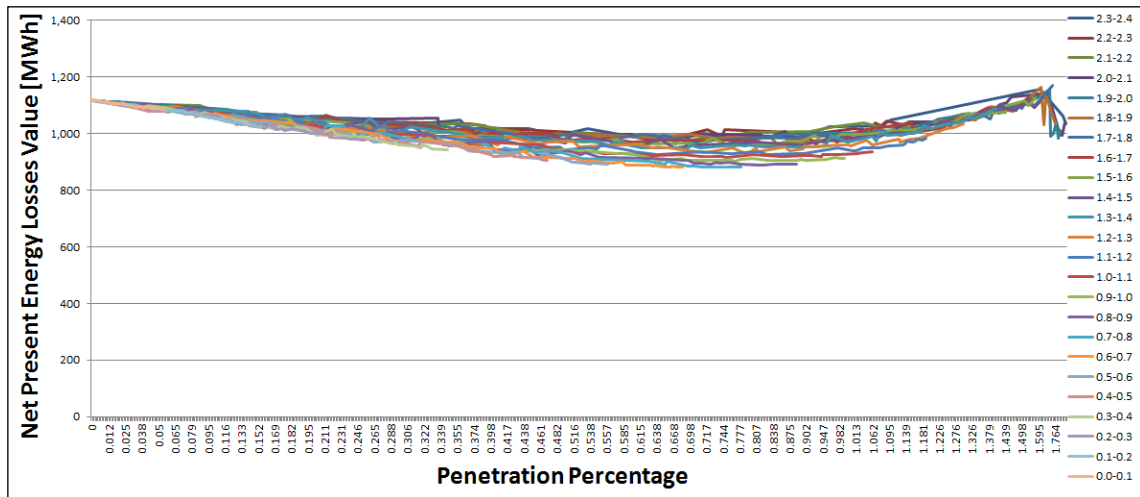


Figure 5-25: Net present energy losses on the urban feeder without tap changer

The base case losses are 1.110 Net Present MWh while the lowest losses case marked 880 Net Present MWh's as the lower bound for a 70 % of penetration and a behavior interval of 0.6-0.7 p.u.. This means a 21 % decrease in losses only generating during low use of system hours, because the demand peak occurs around 10 pm. This idea opens a discussion to think about the economical signal of losses that the current regulation gives. Distributed generators are paid the energy price at distribution level, plus the average avoided losses that a system has, in a non-installed DG basis. But what happens if the expected avoided losses are less than the actual ones. We would be overpaying the generators for something that they didn't avoid. A natural response would be the creation of a time variant average losses expansion coefficient, which would give better market signals to the private DG investors. Figure 5-25 also illustrates the "u" shaped losses curve widely mentioned in the DG literature.

5.1.2.1.2 With Tap Changer

The urban tap changer base case presents 1.000 Net Present MWh Value losses for the four year operation of the feeder (non-tap changer base case had 1.100 MWh losses), reaching its lowest values for the a 70 % penetration scenario and 0.6-0.7 behavior scenario with 793 Net Present MWh losses, followed by the 0.7-0.8 behavior scenario, also close to the 70 % penetration mark. Figure 5-26 shows the operation losses of the urban case with tap changer:

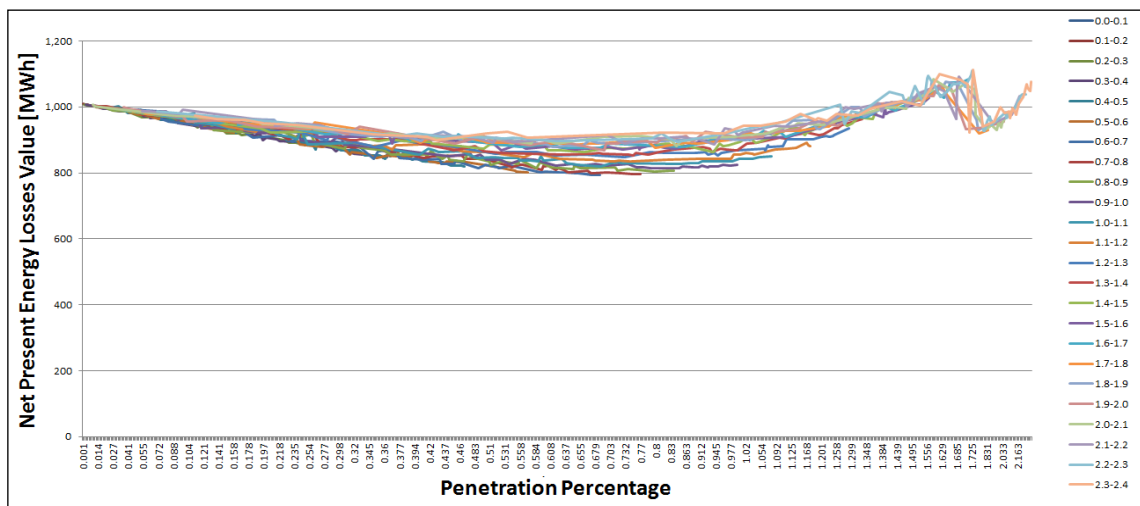


Figure 5-26: Net present energy losses value for the urban feeder with tap changer

5.1.2.2 Rural

5.1.2.2.1 No Tap Changer

DG helps lowering the Net Present Value of losses, from a base case maximum of 354 MWh, to a minimum of 278 MWh, under the 0.7-0.8 behavior interval at a 77 % of penetration. This means that a 21 % decrease in losses can be achieved with non-extreme behavior scenarios. The same decrease in losses was achieved for the urban

case without tap changer with a behavior interval of 0.7-0.8 and a penetration percentage of approximately 70 %. This means that the urban case needs less penetration of DG, under the same behavior interval, to achieve the minimum losses of operation. Figure 5-27 shows the distribution of Net Present Energy Losses for the rural feeder without tap changer.

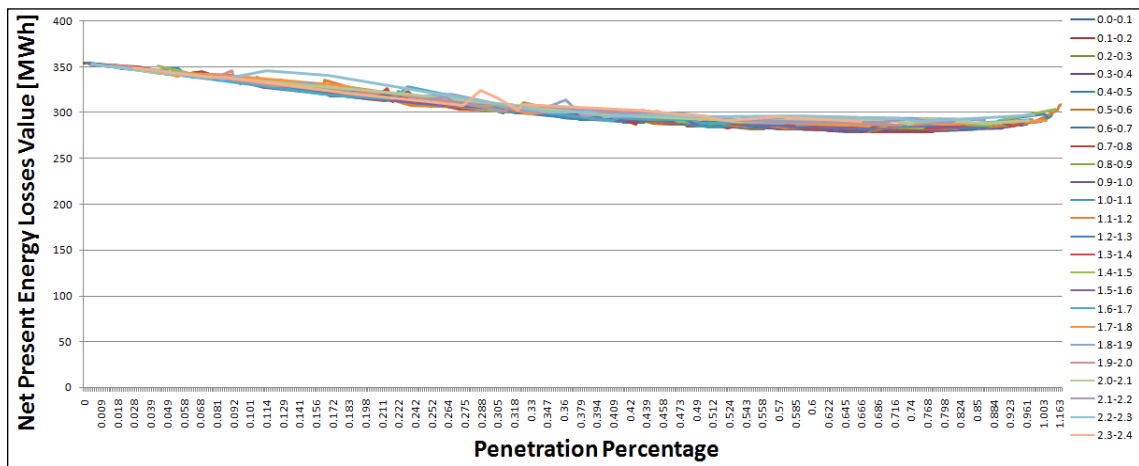


Figure 5-27: Net present energy losses value on the rural feeder without tap changer

5.1.2.2.2 With Tap Changer

The rural case with tap changer was able to lower the Net Present Energy Losses value from 332 MWh without DG penetration to 261MWh at the 0.7-0.8 behavior interval, representing a 21 % decrease in losses (Figure 5-28).

The tap changer rural case allows higher penetrations to be feasible; hence the "u" shaped curve is completely seen for this case, in contrast with the non-tap changer case where only a decreasing losses curve is achieved.

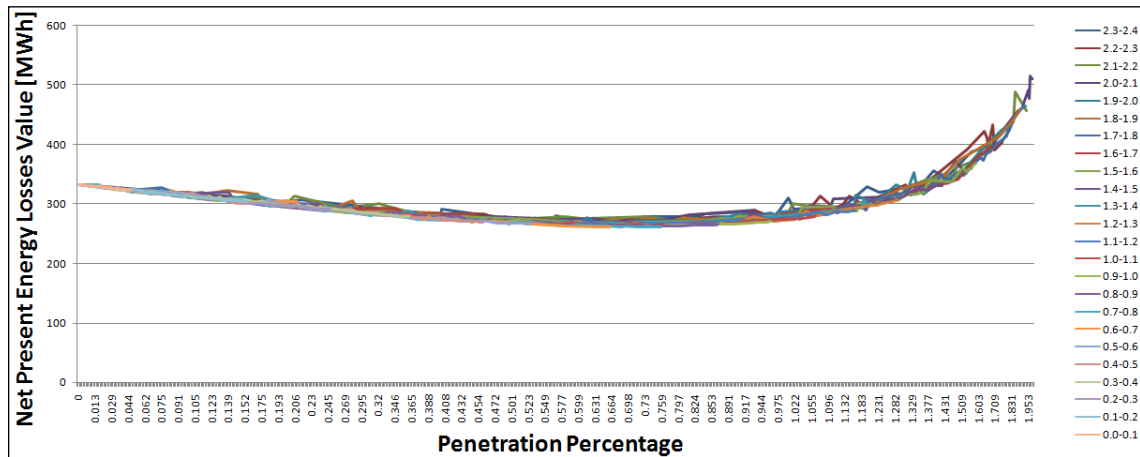


Figure 5-28: Net present energy losses value on the rural feeder with tap changer

5.1.2.3 Indirect DG impact on losses

The presented operational model ensures that no thermal capacity of any series element of the network is violated by upgrading the installed components. These improvements on the network create an indirect impact on losses. When using a certain cable technology, i.e. AASC conductors, higher capacity cables mean a cable with a larger cross section but also lower electric resistance, which has lower operational losses in comparison with his predecessor; hence the network will present lower losses, which will be present during the entire operation of the cable, day and night. This cable will be also working during the peak demand period.

Figure 5-29 shows how the penetration of DG produces a decrease in non-solar day losses (7 pm to 5 am), where base case losses were 616 net present MWh, achieving 433 net present MWh (30 % decrease) for a 184 % penetration scenario. After this penetration point a mayor conductor change is done at the network, producing an important decrease in losses (total losses decreased to values lower than the base case).

An extreme scenario of 252 % produced 311 net present MWh in losses (49 % reduction).

Figure 5-29 presents results for behavior interval 1.5-1.6 and higher. This is the lower behavior interval that triggers capacity related investments. This decrease in losses not only impacts energy purchase but also power purchase by lowering the peak demand that is used to charge the DNO for power consumption. Figure 5-30 shows the energy losses for both solar and non-solar hours of the day, where the characteristic “u” shaped curve appear for the solar hour curves, while the non-solar hour curves present negative slopes that increase in magnitude along with the increase of penetration. This figure also illustrates, during solar hours, the initial decrease of energy losses for low penetration scenarios because lower apparent demand that low penetration of DG creates. This losses reach a minimum point, were the apparent demand is minimum. After this point losses start to increase because of the surplus power that is injected back to the network and has to travel to other consumption points and back to the feeder's header and upstream to higher voltages.

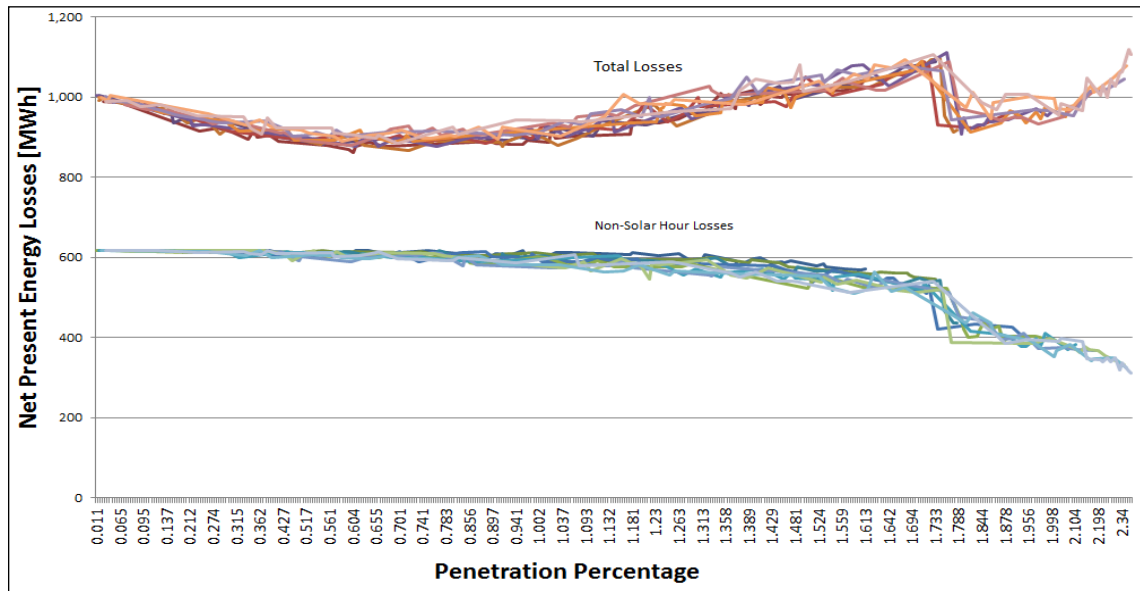


Figure 5-29: Non-Solar Day and Total Net Present Energy Losses

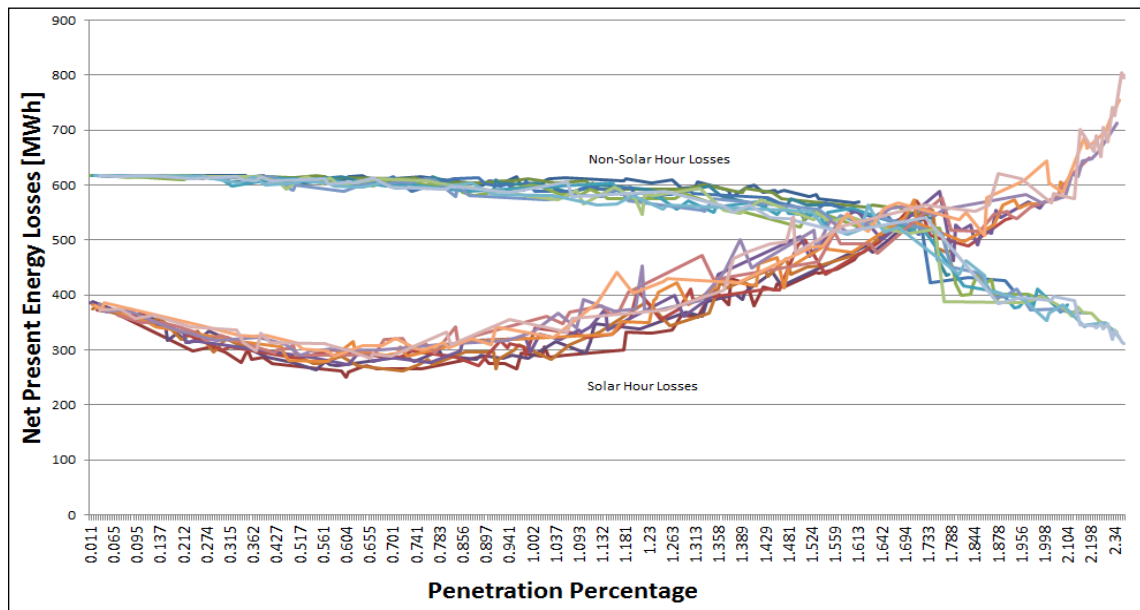


Figure 5-30: Solar & Non-Solar Hour Energy Losses vs. Penetration Percentage

5.1.3 Power Flows on Transformers

Apart from voltage stability and power losses, embedded generation changes the way power flows behave on the network, in terms of magnitude and direction. Not only active power flows suffer changes (considering that solar panel inverters work at unitary power factor) but reactive power flows too. This is due the fact that active power injections cause a voltage phasor angular opening at the extreme buses of a branch that experiences a decrease of active power flows. This angular difference increases throughout the solar day, decreasing once the magnitude of the radiation starts to decrease and the generation to demand ration decreases. Annex 6 presents the analysis of this phenomenon.

The following section will analyze the results obtained for the urban and rural feeder with and without tap changer.

5.1.3.1 Urban Feeder

Figure 5-31 presents the hourly profile of active power flows through the feeder's header for the different penetration scenarios, ranging from 0 % to 81.4 %. This figure lets us know that penetrations as low as 48 % produce inversions of active power flow at the feeders header.

Current net metering legislation in Chile tries to keep the inversion of flows at the lower voltage section of the network, avoiding active power flows back to the medium voltage network. This implies that only low penetration scenarios are going to be feasible under this legislation, pushing the decisions for serious distributed resources legislation further in to the future.

Figure 5-32 presents the active power flows for the different penetration scenarios at the low voltage distribution transformer, showing a similar-shaped curve as the feeder's header chart. At the medium-low voltage interface of the network the penetration scenarios required to invert the power flows are lower, because there are less clients that can consume the injected solar power. This means that the allowed penetrations of the coming Chilean net metering law will allow for fairly low penetrations scenarios to be feasible. This law never talks about a fixed value of penetration, but the assumption of non-inverting power flows at the low voltage distribution comes in hand with low penetration values.

Another impact that DG investigators are worried about is the separation bus bar voltage angles that comes in hand with active power injections. This effect makes electric networks consume more reactive power, increasing the overall apparent power from the feeder's header downstream. Figure 5-33 shows the impact at a distribution transformer that presents inversion of active power flows (line plot) and the percentage of reactive power flows through the distribution transformer (area plot). The magnitude of the change of reactive power flows through the distribution transformer (showed in the purple area) reaches a value of 11 % for a penetration scenario of 81 % and a behavior interval of 5 p.u.. The effect of greater reactive consumption from the network is detected when the low voltage section has a surplus of active power and exports it upstream in to the medium voltage section of the network. Negative reactive power flow variations are also detected in the afternoon, when solar generation is lowering and consumption is increasing.

When reactive power variations are measured at the feeder's header the result shows that the global impact of the penetration of DG only reaches a value of +1 % (grey area in Figure 5-34). Another effect that Figure 5-34 shows is that the solar penetration decreases the reactive power flows that the network consumes (grey area) for low penetrations or hours of the day when solar panels do not inject so much power relative to the consumption. Figure 5-35 shows how, under low penetrations scenarios, the reactive power that the network consumes decreases, meanwhile high penetration scenarios present negative variations for the starting and ending hours of the "solar daily cycle" and positive for the peak generation periods.

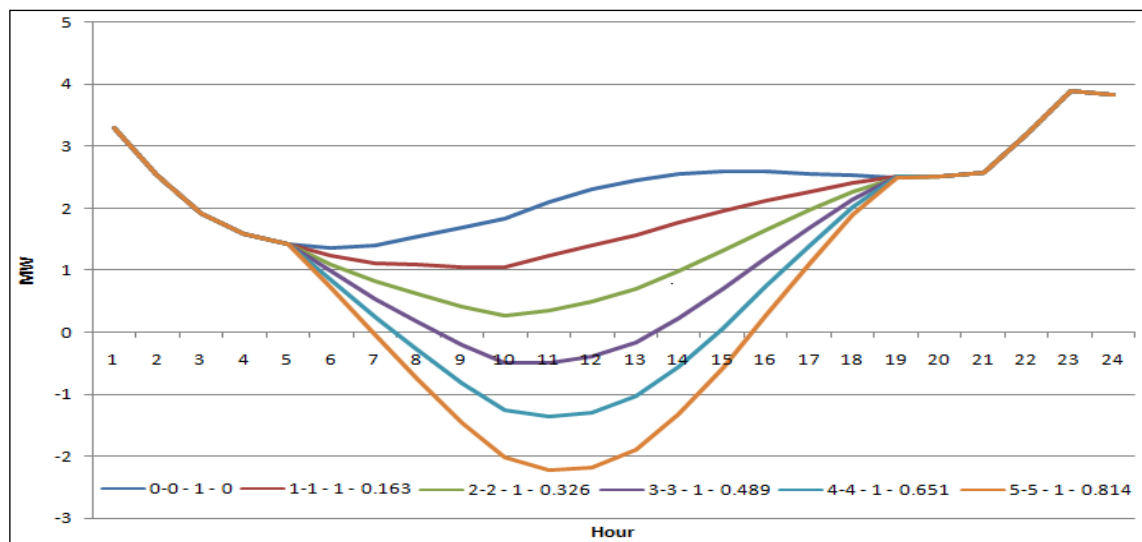


Figure 5-31: Active power flow at the urban feeder's header without tap changer for the different penetration scenarios

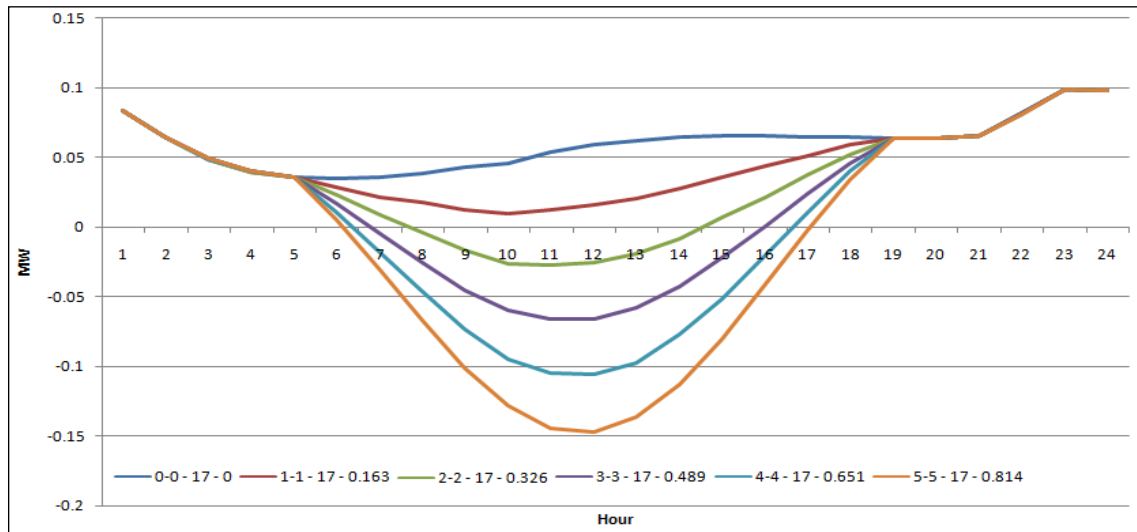


Figure 5-32: Active power flow at a low voltage distribution transformer for the different penetration scenarios

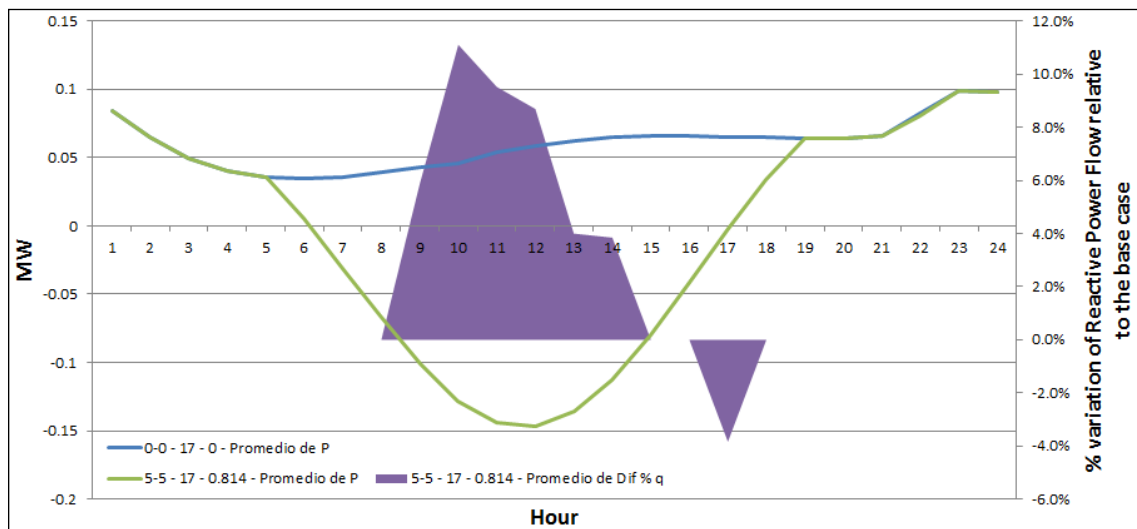


Figure 5-33: % change of reactive power flow through the distribution transformer relative to the base case without DG for a penetration scenario of 81 %

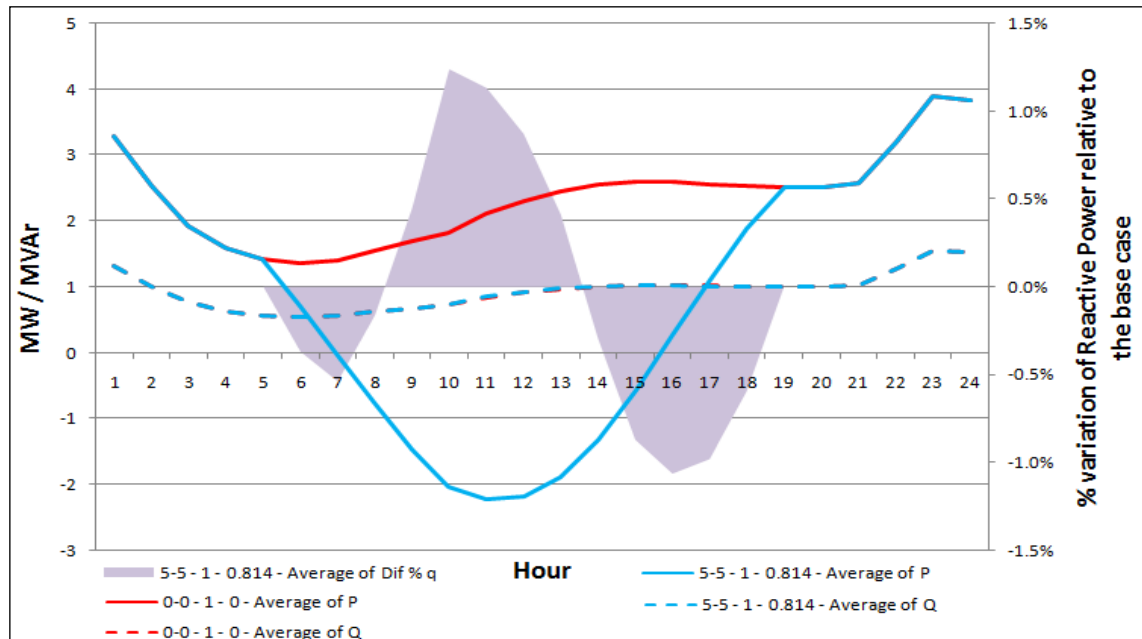


Figure 5-34: Active and Reactive Power Flows at the feeder's header and % of variation of Reactive Power Flows relative to the base case without DG for a penetration scenario of 81 %

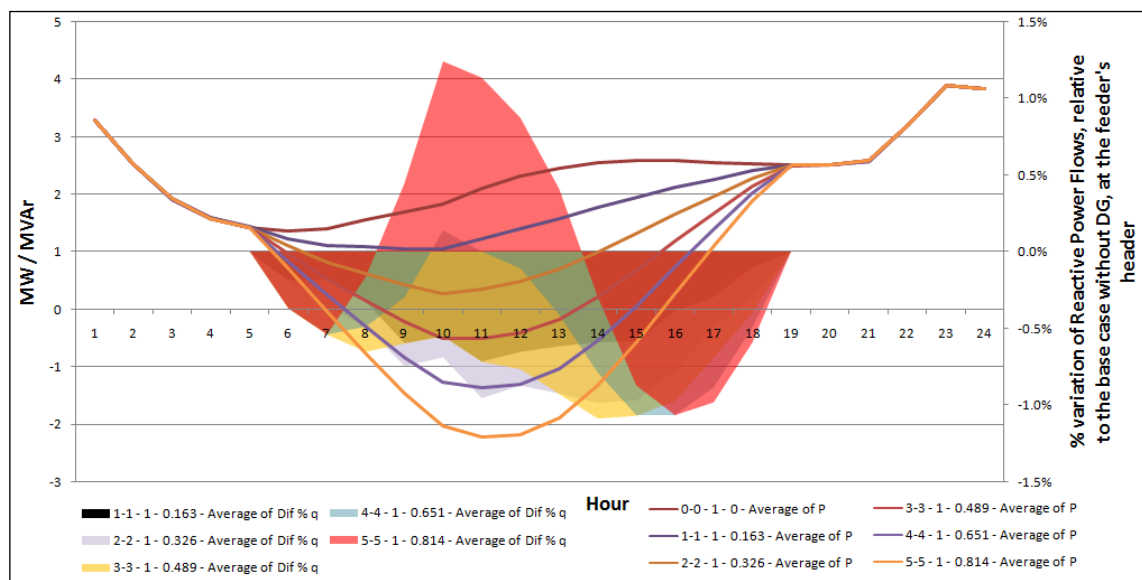


Figure 5-35: Active and Reactive Power Flows and % of variation of Reactive Power Flows relative to the base case without DG for different penetration scenarios

The urban case with tap changer allows higher penetrations to be feasible letting better understanding of the behavior of the power flows at the feeder's header and distribution transformers under high penetrations of DG to be achieved. Figure 5-36 shows the active power flows at the feeder's header for different penetrations scenarios, achieving an extreme penetration scenario of 228 %. Active power flows are inverted at penetration scenarios of 48.9 % and higher. Figure 5-37 shows how the active power flows behave under the same penetration scenarios at a distribution transformer.

Once again we analyze the behavior of the reactive power consumption done by the network at the distribution transformer level. Figure 5-38 shows the consumption of active and reactive power plus the percentage of variation of reactive power in comparison with the base case. The 228 % penetration scenario presents an increase of 80 % of the reactive power downstream of the distribution transformer that presents embedded generation.

Figure 5-39 shows the same exercise at the feeder's header, where it can be seen that an increase of 26 % was registered at 11 am for the penetration scenario of 228 %.

When the escalated penetrations are analyzed, it can be seen how the reactive consumption from the network changes relative to the penetration (Figure 5-40). This figure shows that there is no reactive power flow variation lower than -1 %, meaning that the decrease in reactive consumption is only achieved for low penetration scenarios and the magnitude of it is low.

Even though a 26 % of increase of reactive power from the network is a significant change, the driver of this change is the active power variation, which already by itself triggers capacity changes throughout the network. This tells us that variation in reactive

power is important, but the main variable that drives the thermal capacity changes is the active power.

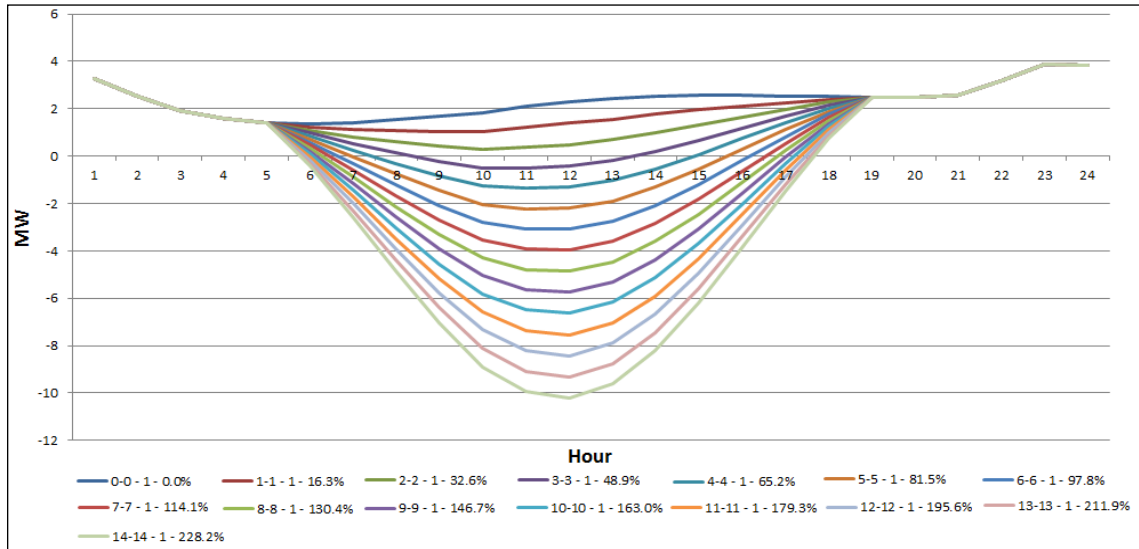


Figure 5-36: Active power flow at the urban feeder's header with tap changer for the different penetration scenarios

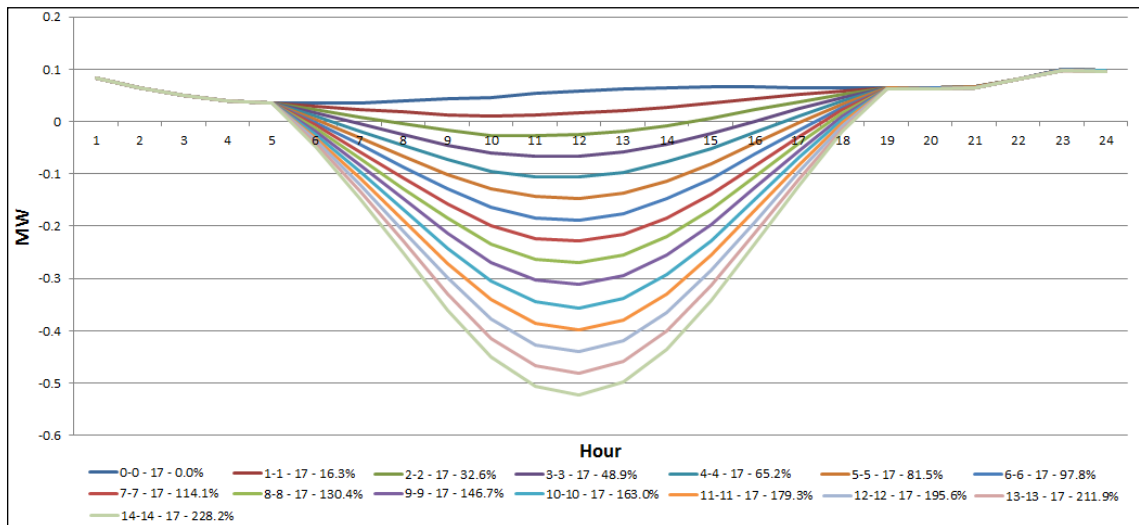


Figure 5-37: Active power flow at a low voltage distribution transformer for the different penetration scenarios

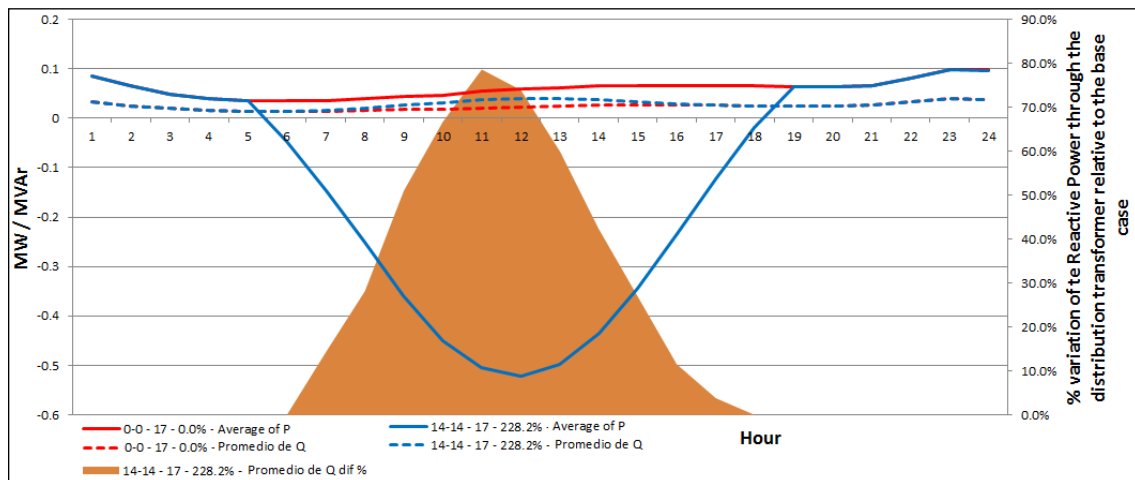


Figure 5-38: Active and Reactive Power Flows at a distribution transformer and % of variation of Reactive Power Flows relative to the base case without DG for a penetration scenario of 228 %

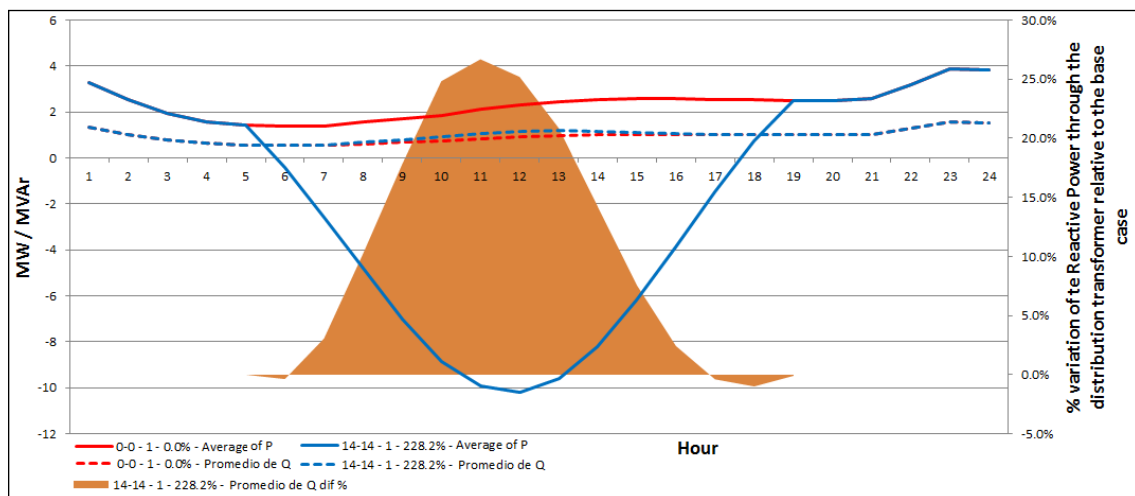


Figure 5-39: Active and Reactive Power Flows at the feeder's header and % of variation of Reactive Power Flows relative to the base case without DG for a penetration scenario of 228 %

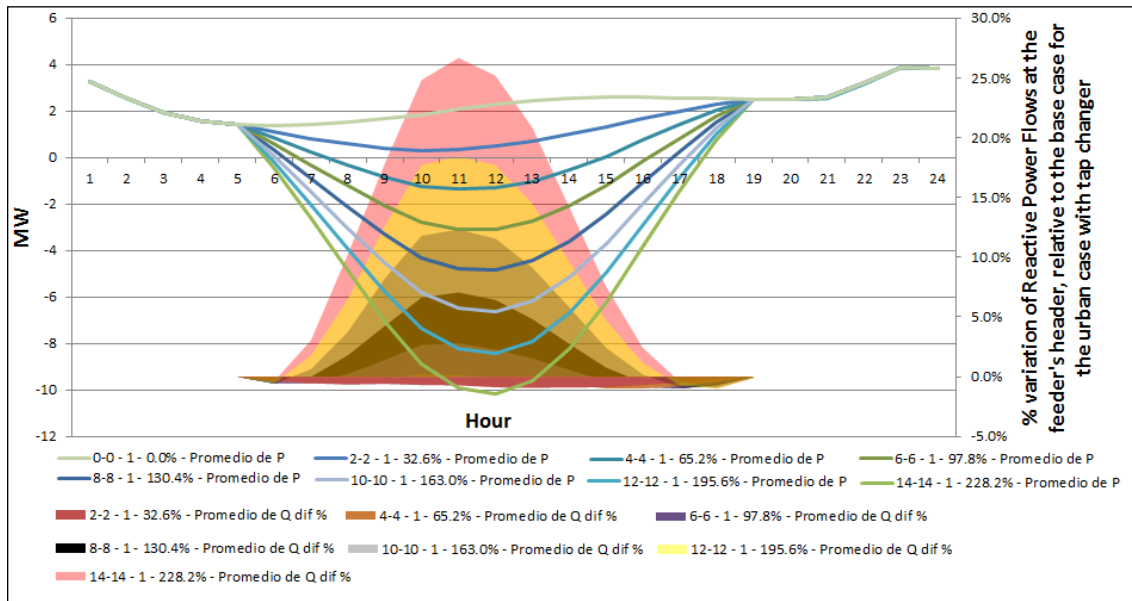


Figure 5-40: Active and Reactive Power Flows at the feeder's header and % of variation of Reactive Power Flows relative to the base case without DG for different penetration scenarios

5.1.3.2 Rural Feeder

The rural feeder without tap changer, with its low penetration feasibility, only shows the low penetration effects of the embedded generation. Figure 5-41 shows the active power flows at the feeder's header, where it can be seen that the low penetrations could barely invert the active power flows at the feeder's header. Figure 5-42 shows as an example the active power flows at one of the distribution transformers for the different penetration scenarios where, for the specific example, no inversions of active power flows, were detected. Given the low embedded power generation installed downstream from this distribution transformer, the impact on the reactive power consumption from the network was immeasurable for the model (Figure 5-43), meanwhile the summed up effect of the embedded generation at the feeder's header can be seen in Figure 5-44,

where a decrease in reactive power was detected. This variation reaches a value of -1.7 % (for a 38 % of penetration) relative to the base case without embedded generation. The impacts of the different penetration scenarios on the reactive power consumption are shown in Figure 5-45. Only negative variations of reactive power can be seen, because of the low penetration scenarios.

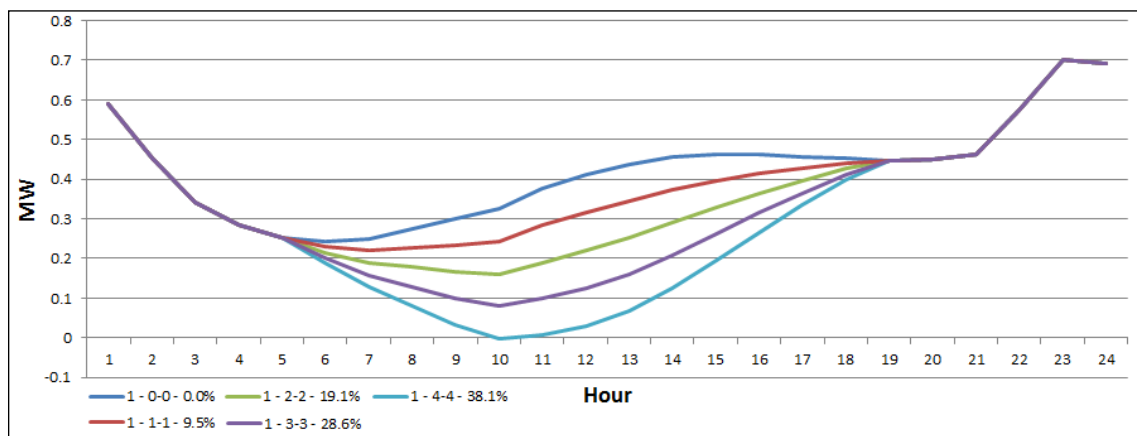


Figure 5-41: Active power flow at the feeder's header for the different penetration scenarios for the rural case without tap changer

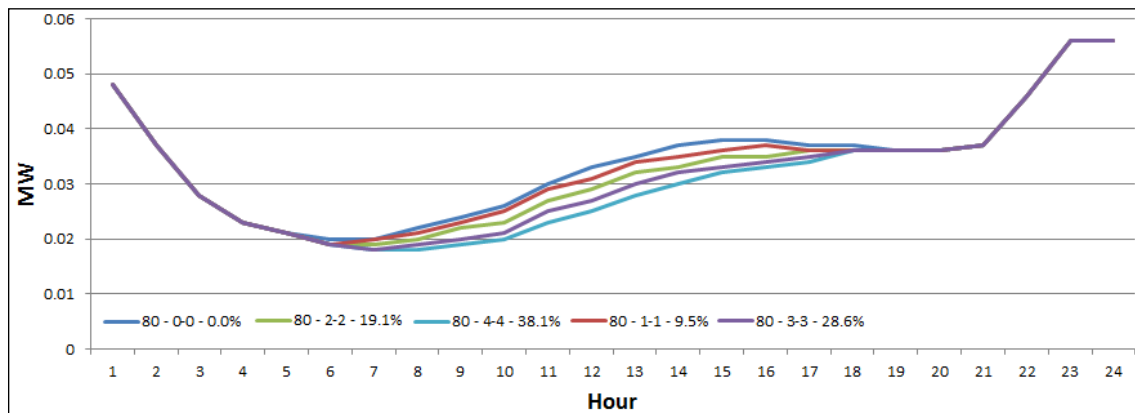


Figure 5-42: Active power flow at a low voltage distribution transformer for the different penetration scenarios

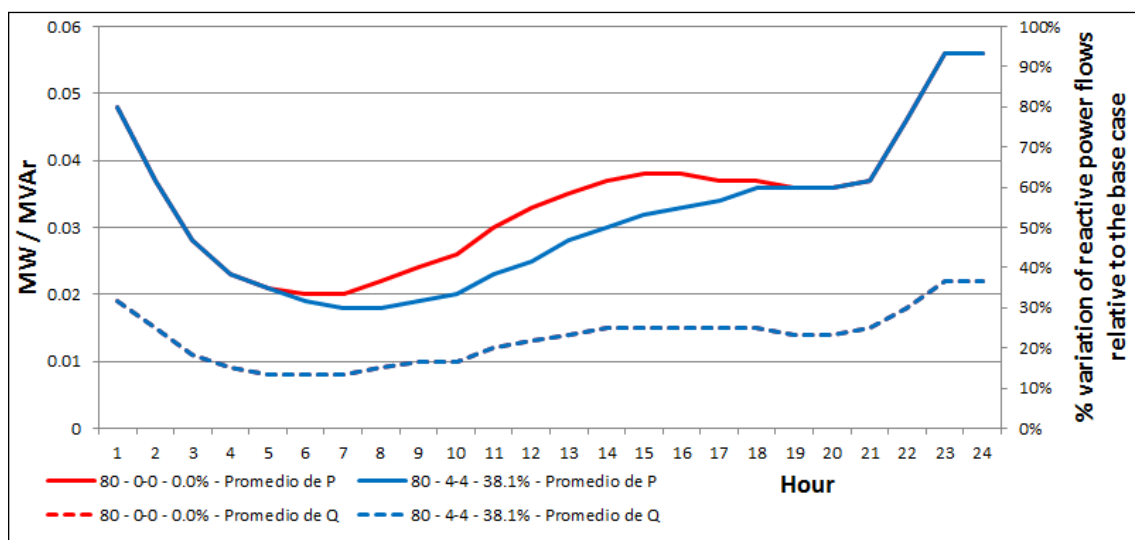


Figure 5-43: Active and Reactive Power Flows at a distribution transformer and % of variation of Reactive Power Flows relative to the base case without DG for a penetration scenario of 38.1 %

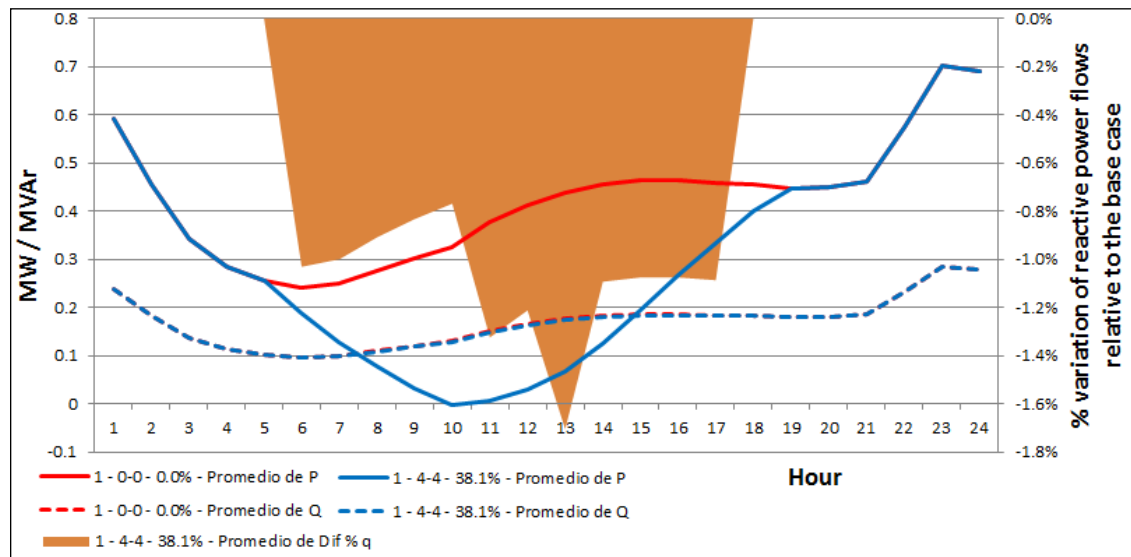


Figure 5-44: Active and Reactive Power Flows at the feeder's header and % of variation of Reactive Power Flows relative to the base case without DG for a penetration scenario of 38.1 %

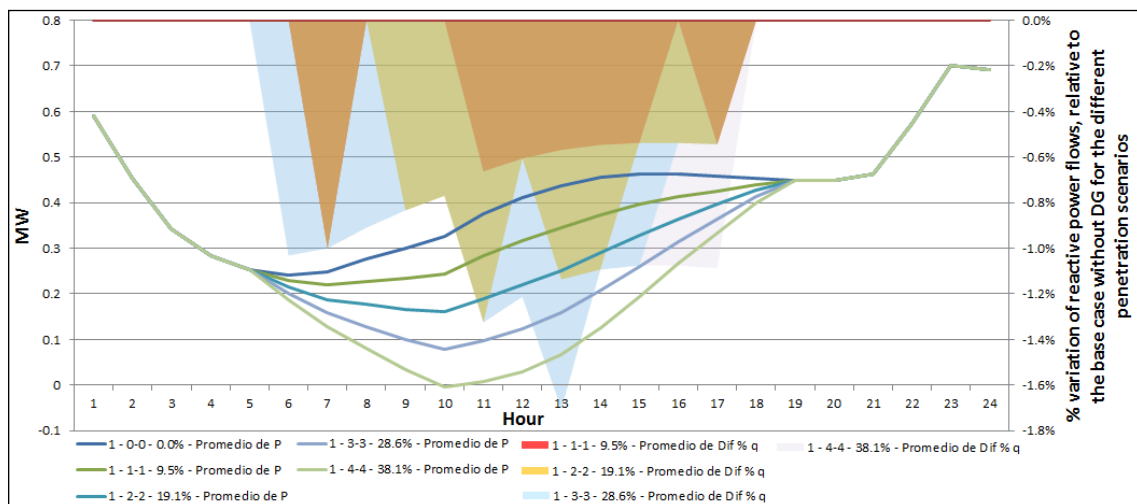


Figure 5-45: Active and Reactive Power Flows at the feeder's header and % of variation of Reactive Power Flows relative to the base case without DG for different penetration scenarios

The rural case with tap changer enables a 57.1 % of penetration of DG to be feasible, allowing us to understand how more penetration affects the active and reactive power flows at the distribution transformers and the feeder's header. Figure 5-46 presents the

active power flows at the feeder's header, that present inversion of flows for a 47 % of penetration and higher.

Figure 5-47 presents the active power flows at a distribution transformer that didn't present inversion of active power flows for the different scenarios of penetration, while Figure 5-48 shows the active and reactive power flows for the same distribution transformer. Yet again, given the low penetrations scenarios, the reactive consumption of the network presents no measurable differences. The same exercise is done at the feeder's header, showing in Figure 5-49, a different curve of reactive power flow variation in comparison with the case without tap changer. This is due the fact that higher penetrations mean inversions of active power flows, which passed certain threshold impact increasing the reactive power consumption of the network. Figure 5-50 shows these variations of reactive power flow for the different penetration scenarios. No positive variations of reactive power are detected, because of the low penetrations achieved in the rural feeder with tap changer.

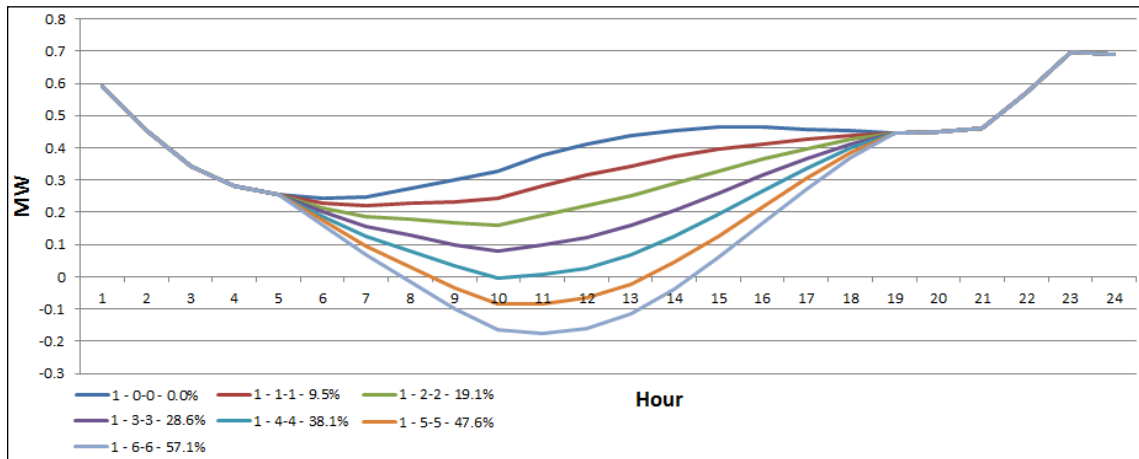


Figure 5-46: Active power flow at the feeder's header for the different penetration scenarios for the rural case without tap changer

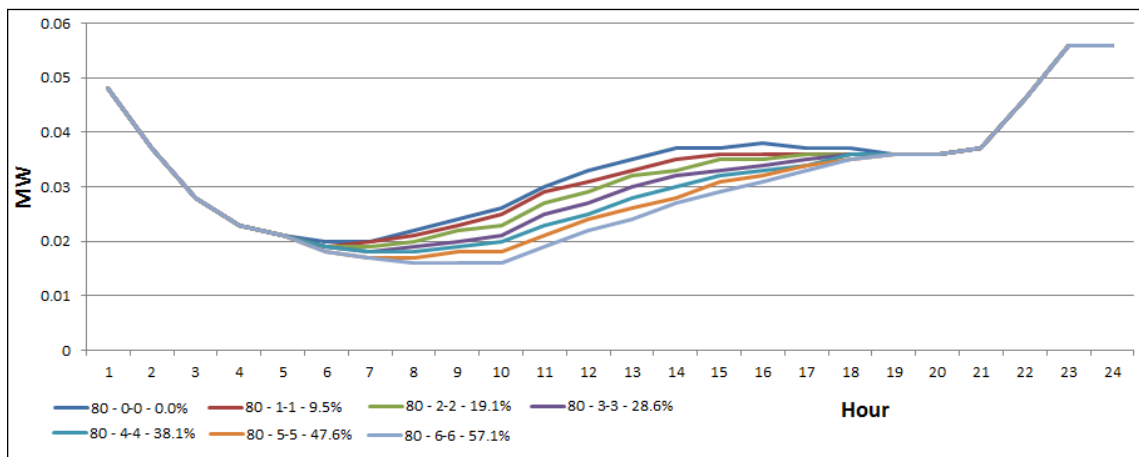


Figure 5-47: Active power flow at a low voltage distribution transformer for the different penetration scenarios

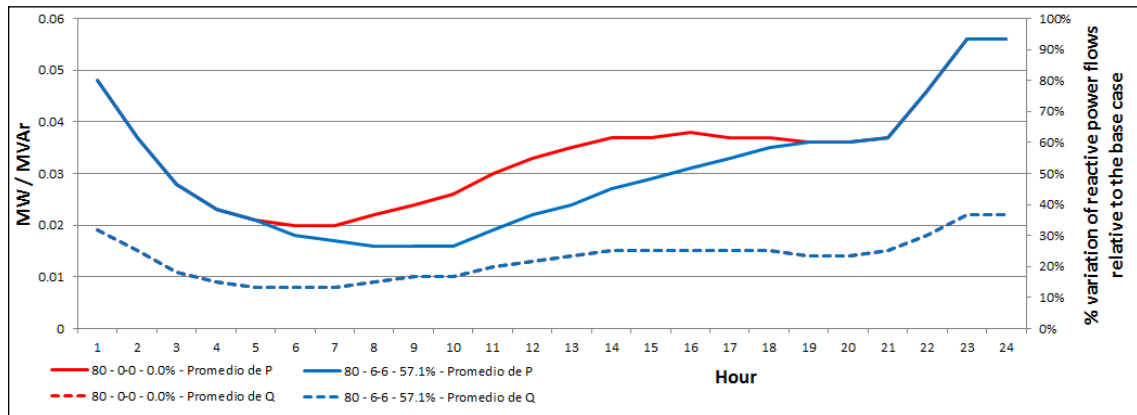


Figure 5-48: Active and Reactive Power Flows at a distribution transformer and % of variation of Reactive Power Flows relative to the base case without DG for a penetration scenario of 57.1 %

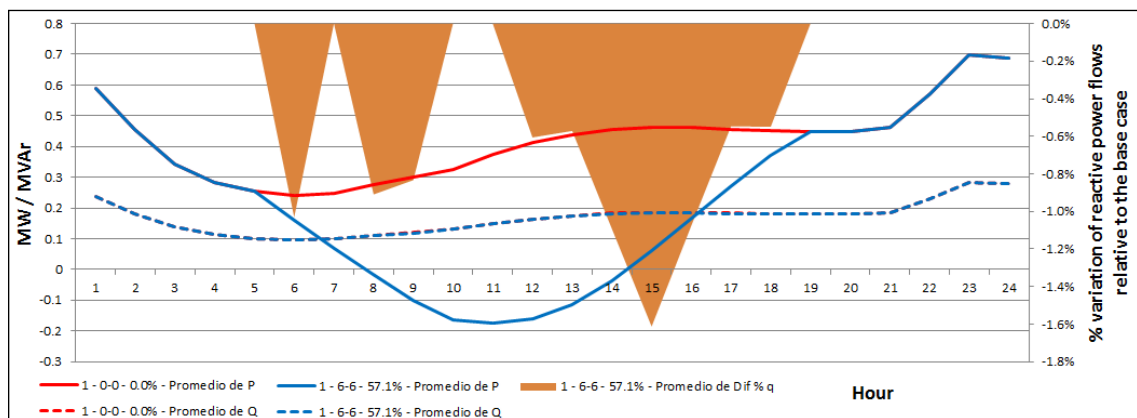


Figure 5-49: Active and Reactive Power Flows at the feeder's header and % of variation of Reactive Power Flows relative to the base case without DG for a penetration scenario of 57.1 %

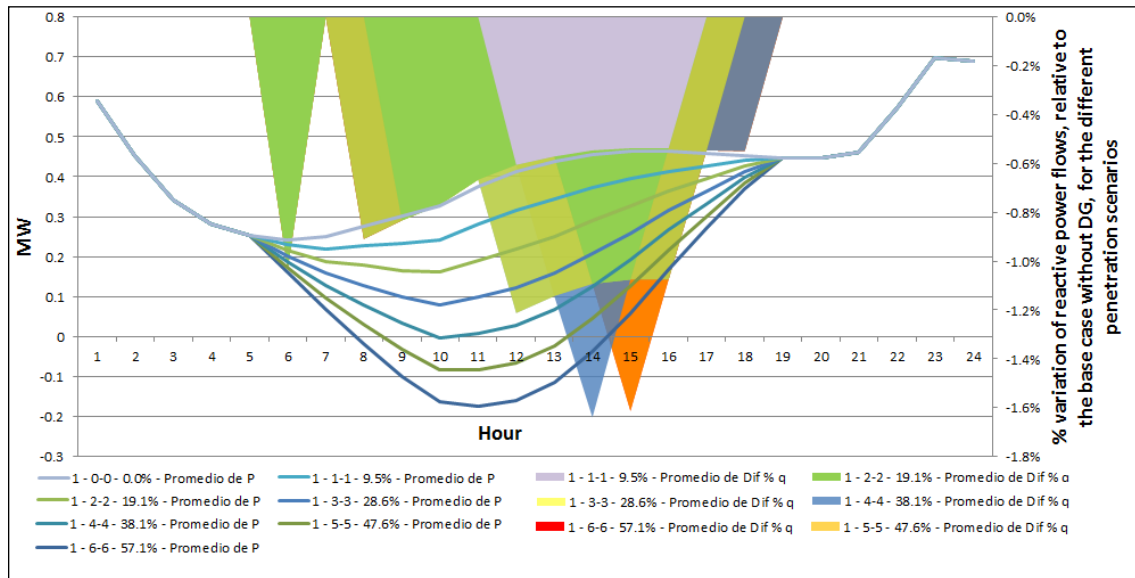


Figure 5-50: Active and Reactive Power Flows at the feeder's header and % of variation of Reactive Power Flows relative to the base case without DG for different penetration scenarios

5.2 Operational Results

This section discusses the economic operational outcome of the four year simulation of the different DG penetration scenarios, paying close attention, firstly, to the capacity related investments that the distribution company has to incur in order to meet security constraints of operation and how this costs are transferred to the clients. Secondly, actual tariffs are used to simulate the economic operation of the distribution company, simulating calculating the incomes and costs with the load flow model.

5.2.1 Capacity

In order to understand the phenomenon of the capacity related expenditure and its cost for distributed generation owners and distribution companies, this section analysis the net costs of installing DG and its ratios relative to the installed kW's and kWh's sold to

regulated clients. These two ratios represent the two extremes on how to cover these additive capacity related expenditures.

The cost per installed kW shows how deep connection charges could affect the economic viability of DG, while a socialized cost per kWh gives signals of a shallow or practically nonexistent connection fee, allocating the cost over all the regulated clients.

5.2.1.1 Cost per kW and kWh

The maximum stress caused by solar power injections is caused during the first year of the study horizon, the month with highest radiation and the hour with highest radiation to consumption ratio. For this model it is year one, January at 10 am. Given these parameters, the cost per installed kW was calculated as the total capacity costs divided by the installed kW of DG.

The cost per consumed kWh calculation is done in such a way that a net present income of an extra charge for energy equals the net present cost of the capacity related investments. This index calculation is shown in equation 11.

$$Cost_{kWh} = \frac{\text{Capacity Expenditures}}{\sum_{t=1}^4 \frac{E_t}{(1+r)^t}} \quad (11)$$

Where $Cost_{kWh}$ is the cost per kWh that needs to be paid in order to cover the capacity expenditures for a given penetration scenario for the four year analysis horizon, E_t the energy sold at year t and r the discount rate.

5.2.1.2 Urban

5.2.1.2.1 No Tap Changer

Using a fixed 1 p.u. voltage and 0 % tap position at the feeder's header it was possible to install solar distributed generation till 1.4 - 1.5 p.u. behavior interval, without activating thermal or voltage restrictions, which means no capacity related expenditures were made. Simulations over that threshold of installed capacity behavior show that capacity expenditures are needed. Even more, the higher the behavior interval, the lower the first penetration percentage that triggers capacity investments. This is explained by the fact that higher behavior intervals mean higher concentration of power injections, hence higher use of distribution lines and transformers in specific areas. These capacity related investments can reach up to 250 thousand dollars for the highest penetration scenarios of 199.5 %. For more detail on the capacity related investment distribution see Figure 5-51. Figure 5-52 shows how much DG owners should pay at the moment of the connection to the system for the different behavior and penetration scenarios.

Connection charges range from 0 to 83 US\$ per installed kW depending on the penetration percentage. High connection charges can be seen when low penetrations happen, this happens when specific combinations of DG are installed in low capacity areas of the network. When larger penetrations occur the charges stabilize and stay in the 0-27 US\$/kW band which never is broken for the analyzed behavior intervals. This way of charging for the capital expenditure is called deep connection charges. The other extreme is called shallow connection charges, which charges smaller fees and the full cost is socialized by the distribution company and paid by all the clients with some

criteria. For this exercise the capacity costs will be distributed over all the clients in relationship to their consumption.

Figure 5-53 shows the socialized costs over the sold energy to the regulated clients of the urban feeder.

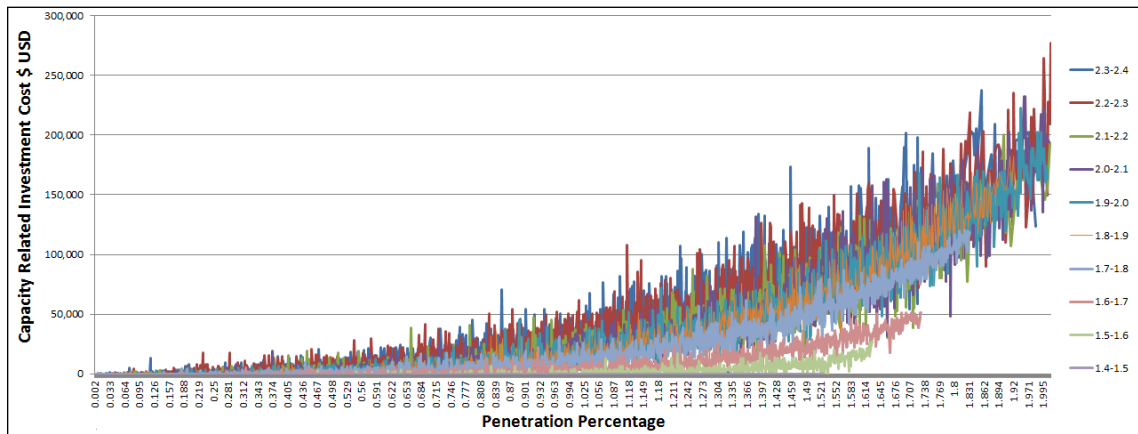


Figure 5-51: Capacity related investment for the urban feeder without tap changer for the different behavior intervals

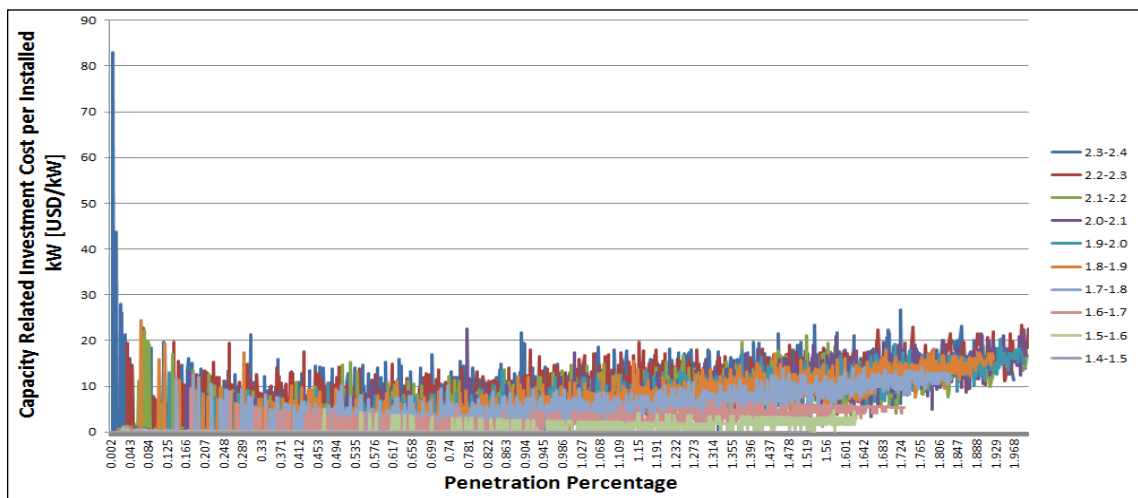


Figure 5-52: Maximum capacity related investment per installed kW for different penetration scenarios

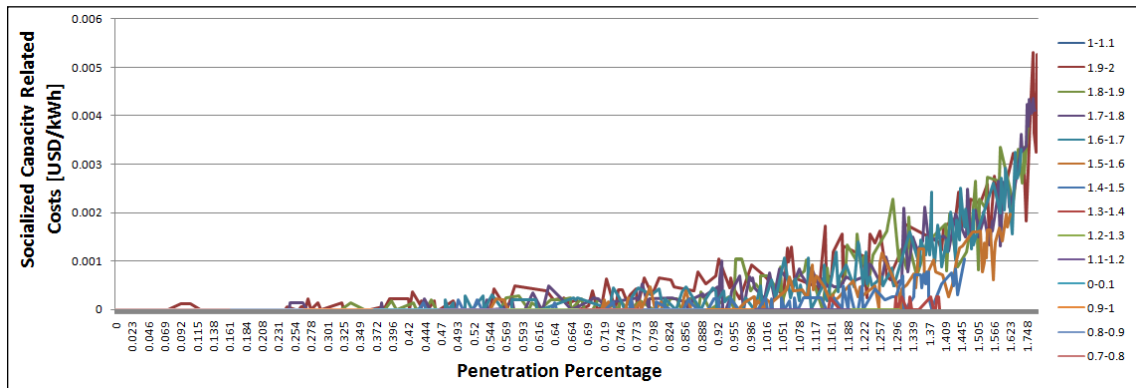


Figure 5-53: Socialized capacity related cost per consumed kWh

The assimilated energized capacity costs stay under the 1 US\$/MWh band, breaking it for the first time at the 92 % of penetration. After this point the costs behaves in a nonlinear way. The highest energized cost reached the 5 US\$/MWh value. These assimilated energized costs mean that all clients have to pay more for their consumed kWhs, even those who haven't installed DG.

5.2.1.2.2 With Tap Changer

The urban case with tap changer allows more DG to penetrate by lowering the voltage set point at the feeder's header during the hours of high generation relative to consumption, avoiding overvoltages on the network bars at every voltage level. The highest DG penetration scenario achieved under the non-tap changer case, was 194 %.The tap changer case achieves 242 % of DG penetration, causing also a different capacity investment outcome. The highest capacity related investment for the non-tap changer case was approximately 250 thousand dollars, vs. 400 thousand for the tap changer case (Figure 5-54).

The cost per installed kW increased because of the higher achievable penetration scenarios. For the non-tap changer case the maximum cost per installed kW was about 20 \$ US\$. For the tap changer case this value rises to almost 30 \$ US\$. If the same penetration interval is analyzed, there is practically no difference between the non-tap changer and the tap changer case, meaning that the tap changer would only allow more DG allocation, but not avoid or defer capacity related investments (Figure 5-55).

When socializing the capacity related cost over the regulated clients energy consumption, the maximum obtained cost per kWh for the tap changer case was 10 \$ US\$/MWh, in comparison with the 5.3 \$ US\$/MWh obtained without the use of tap changer. The difference lies in the amount of feasible penetration that the tap changer allows, increasing the investment related costs. If the same penetration intervals are analyzed, similar values of socialized costs appear on both cases, creating an upper boundary for the 174.8 % and lower of DG penetration of 4.5 US\$/MWh. For more details on the distribution of the internalized cost of capacity related investment costs see Figure 5-56.

The urban feeder with tap changer presents no overvoltages, meaning that a 243 % of DG penetration could be feasible but only after investing 400 thousand dollars in increasing the thermal capacity of the network.

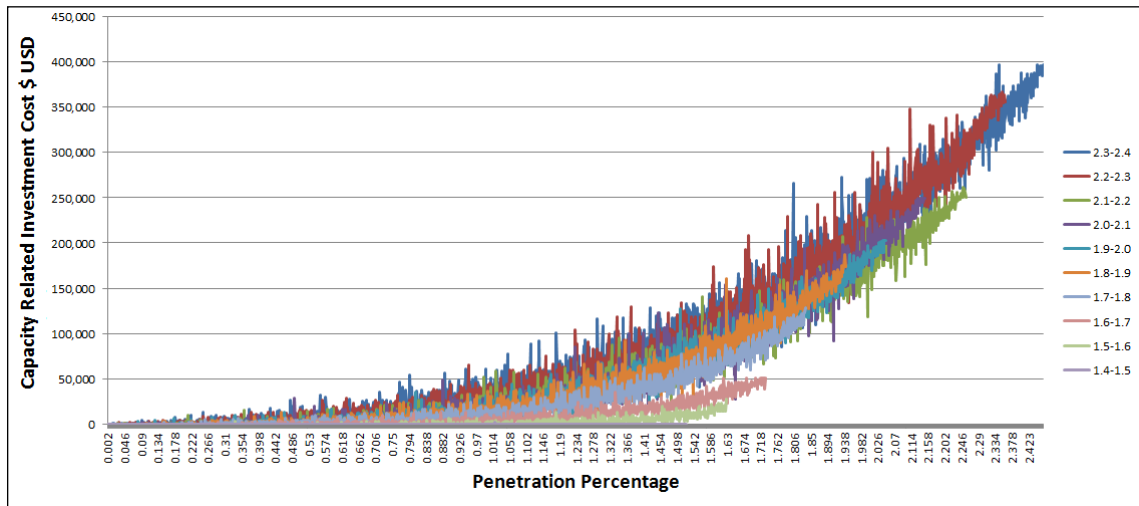


Figure 5-54: Capacity related investment for the urban feeder with tap changer

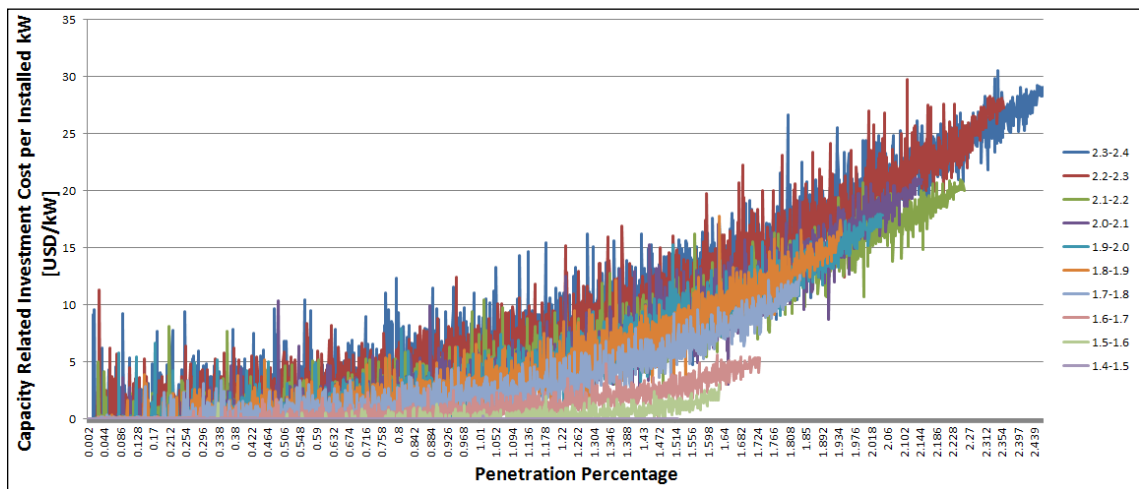


Figure 5-55: Capacity related investment per installed kW for the urban feeder with tap changer

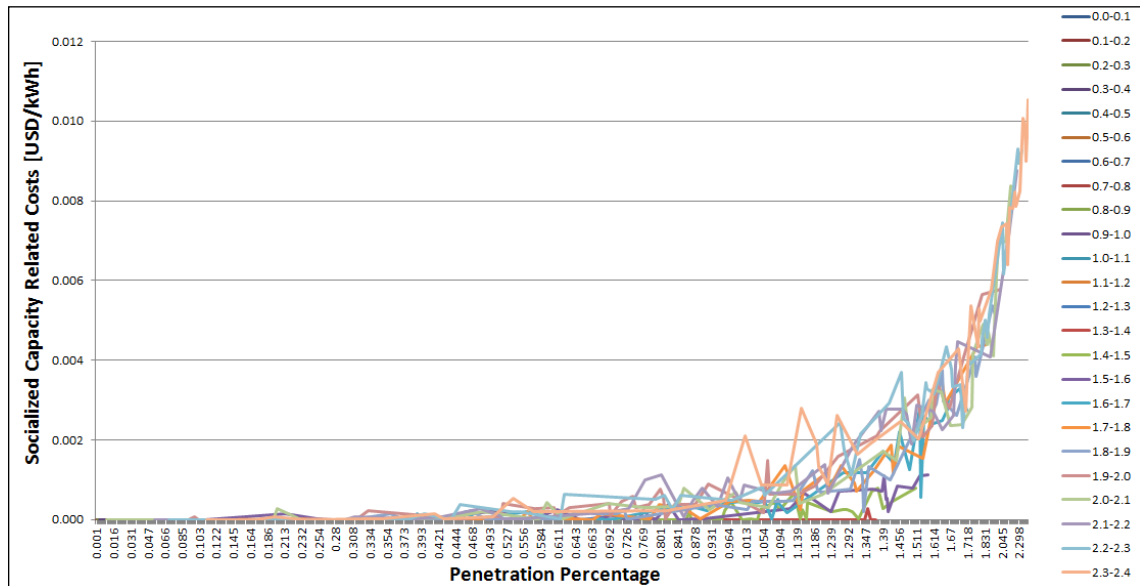


Figure 5-56: Capacity related investment per consumed kWh for the urban feeder with tap changer

5.2.1.3 Rural

5.2.1.3.1 No Tap Changer

After filtering non-feasible scenarios, no combination of behavior interval and penetration caused conductor or transformer capacity changes. This is due the fact that rural networks are oversized in relation to its load because of their size, in order to keep quality standards of voltages over the entire feeder. This is not the case of the urban feeder, where the loads are relatively close and the electric resistance impacts less on the voltage profiles.

5.2.1.3.2 With Tap Changer

Over the 76 % penetration barrier, the rural case with tap changer presents capacity related investments. These costs grow slowly till the 144 % penetration mark, where the rate of growth increases, reaching a cost of 110 thousand dollars in capacity related

investments. This cost is four times lower than the investment needed at the urban feeder with tap changer (considering that the urban feeder is 16 times smaller, in terms of length).

The investment cost per installed kW stays under the 10 dollar band for penetrations under 150 %, after that point costs grow reaching a maximum of 50 dollars per installed kW. This value practically doubles the costs per kW achieved in the urban case without tap changer. The socialized capacity related cost stays under the 2 US\$/MWh band for any penetration scenario under the 140 % barrier, which past that point grows, reaching a value of 11.7 US\$/MWh for a 189 % penetration. The same penetration percentage produced a 4 US\$/MWh cost (three times lower) at the urban feeder case.

The distribution curves of capacity related costs versus can be seen in Figure 5-57, Figure 5-58 and Figure 5-59.

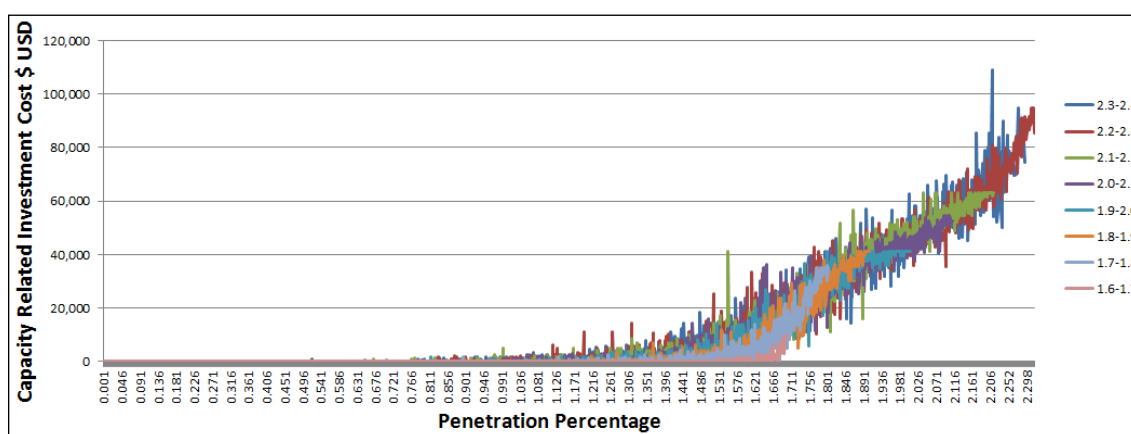


Figure 5-57: Capacity related investment costs for the rural case with tap changer

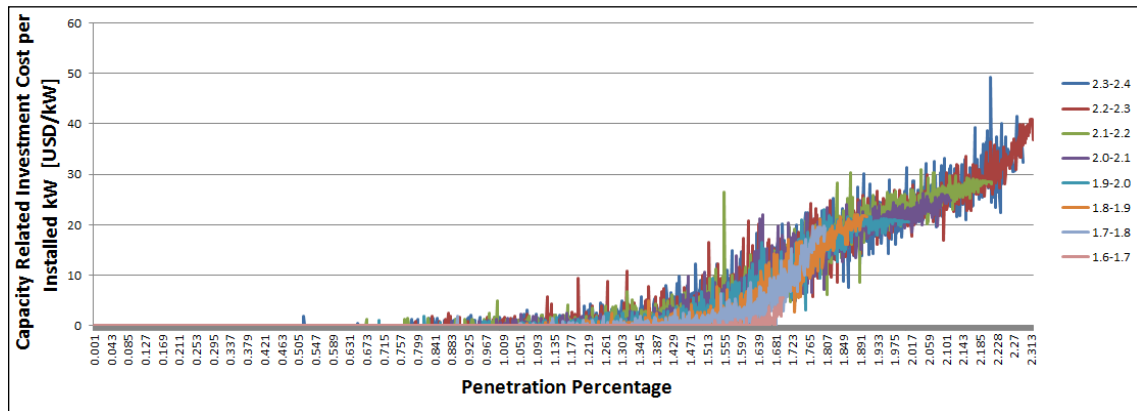


Figure 5-58: Capacity related investment costs per installed kW for the rural case with tap changer

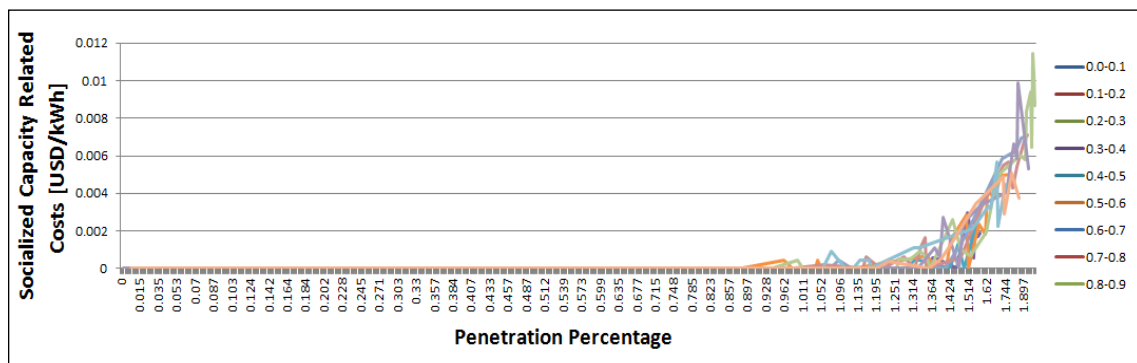


Figure 5-59: Capacity related investment costs per consumed kWh for the rural feeder with tap changer

5.2.2 Economic Operation of the Distribution Company

The operational model simulates a four year regulatory process in which revenues, costs and profits (revenues minus costs) are calculated for the distribution company. This exercise is done for the base case with no installation of DG and for several random DG penetration scenarios and for every analyzed client behavior interval. A performance index, based on variation of profits, is calculated for each penetration scenario, using as base the scenario without DG. This index is calculated for three tariff schemes (BT1,

BT2 and BT1*) in order to better understand the dynamics of the current tariff schemes under DG penetration.

5.2.2.1 Urban

5.2.2.1.1 No Tap Changer

The following figures present the profit variations for the analyzed tariffs (Figure 5-60, Figure 5-61 and Figure 5-62):

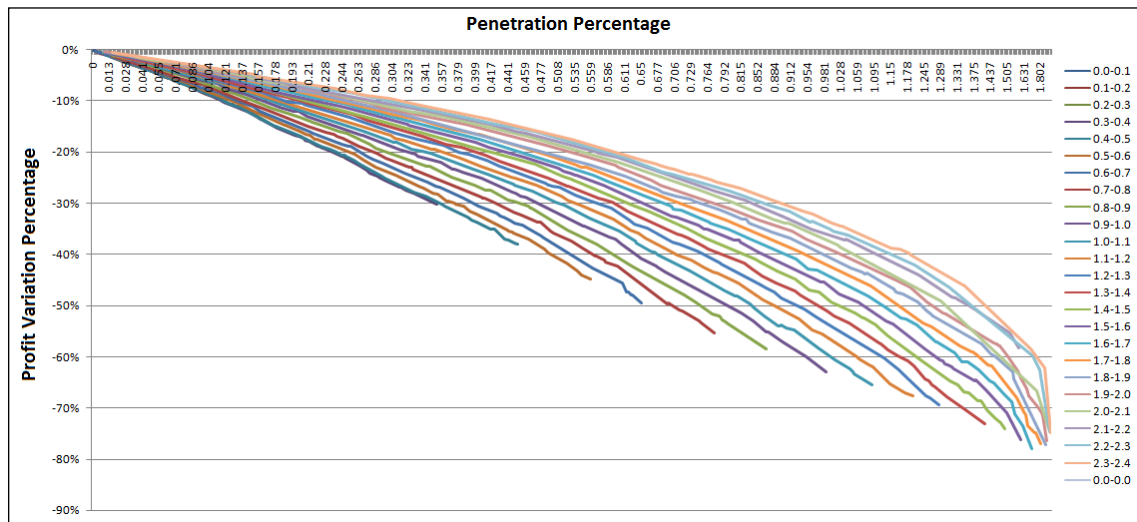


Figure 5-60: BT1 tariff economic operation on the urban feeder without tap changer

The fully energized BT1 tariff presents negative profit variations for any combination of penetration and behavior scenario (Figure 5-60).

For low penetrations scenarios the profit variation curve behaves linearly, as a function of the percentage of penetration, presenting a negative slope that is a function of the behavior interval. This slope presents a lower magnitude for higher behavior intervals, meaning that for a given penetration percentage, the distribution company losses less profits when fewer big clients install a certain amount of kW's than more small clients.

After a certain penetration percentage the differential profit curves suffer a shift in their decline rate, increasing their value, meaning that the higher the penetration percentage at which a PV kW is installed the more impact it will have on the profits of the DNO company. The largest variation of profits occurred on the high behavior intervals that created high penetration percentage values (180 %), reducing the profits related to the base case by a 78 %.

Figure 5-61 presents the same exercise under the BT2 tariff scheme:

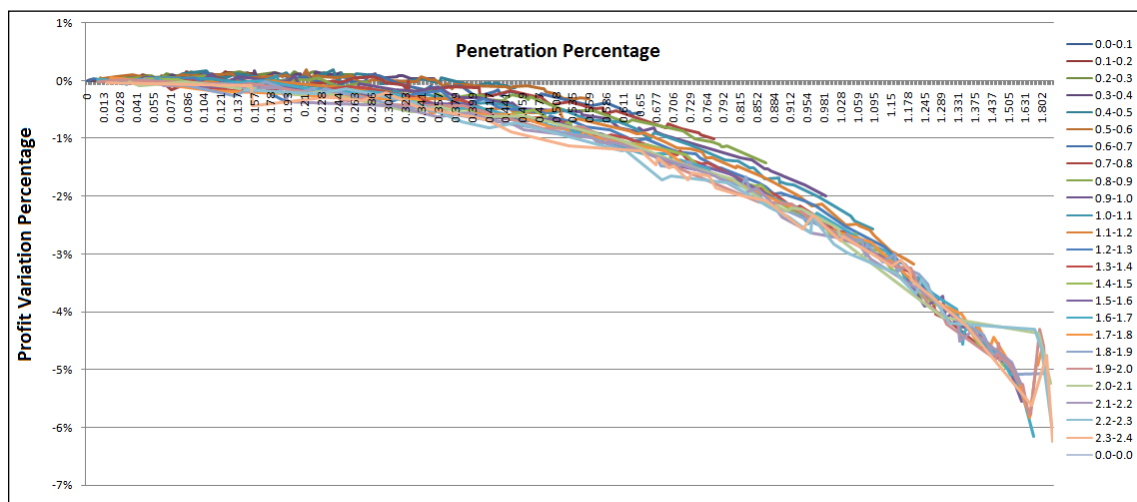


Figure 5-61: BT2 tariff economic operation on the urban feeder without tap changer

The BT2 differential profit curves present a different behavior in comparison with the BT1 tariff. Firstly, for low penetration percentages and low behavior intervals positive profit variations were achieved, where the maximum value was 0.19 %. Secondly, all the curves descend in the same way, increasing the descend rate along with the increase of penetration of PV DG. Another interesting fact about the BT2 tariff is the low and almost non-existent spread between the different behavior interval curves, which is due

the fact that capacity charges are paid in a fixed way, avoiding non-capacity payments which occur on the BT1 tariff scheme. The BT2 tariff scheme helps mitigating the uncertainty of how DG will appear on the distribution grids, although this tariff scheme still presents negative profit variation for some penetration percentage intervals. The largest profit loss reached a value of -6 %, much lower than the BT1 tariff, but still negative.

The proposed, fully energized, BT1* tariff distinguishes the client as a consumer and a generator, charging for the complete consumption and paying for all the generation the energy value fixed by law. Figure 5-62 shows the differential profit curves for the proposed BT1* tariff:

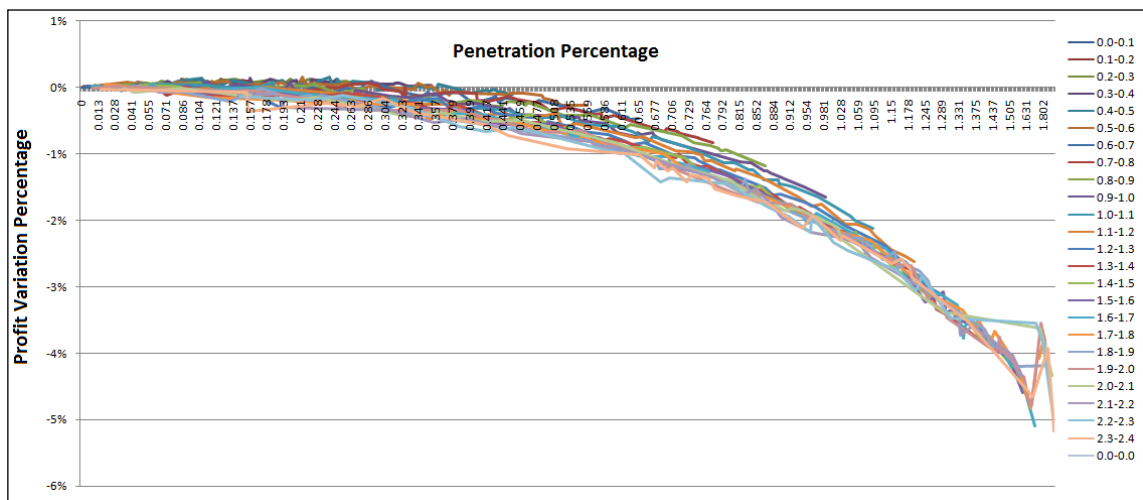


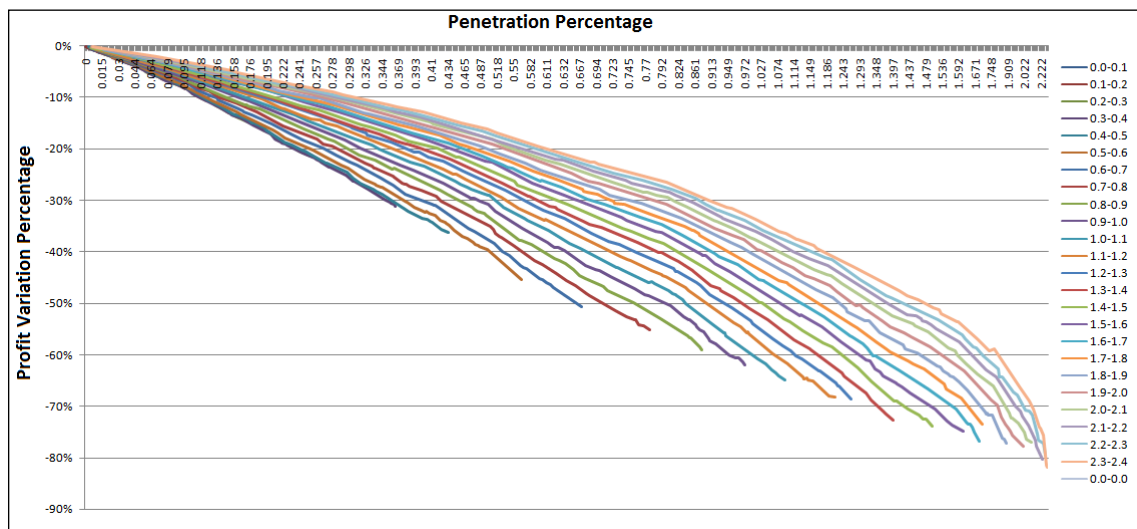
Figure 5-62: BT1* tariff economic operation on the urban feeder without tap changer

The proposed tariff presents a similar behavior as the BT2 tariff scheme, small positive variation for low penetration scenarios and negative variation for higher penetration scenarios with low spread in between the behavior interval curves. The largest profit loss

reached a value of -5 %, 1 % less than the BT2 tariff, opening the possibilities for new tariff schemes to be implemented in the future.

5.2.2.1.2 With Tap Changer

This section shows the results after running the economic operation using tap changer at the feeder's header, which allows higher penetration scenarios to be feasible by lowering the voltage set points at the feeder's header. The BT1 tariff impacts are shown in Figure 5-63:



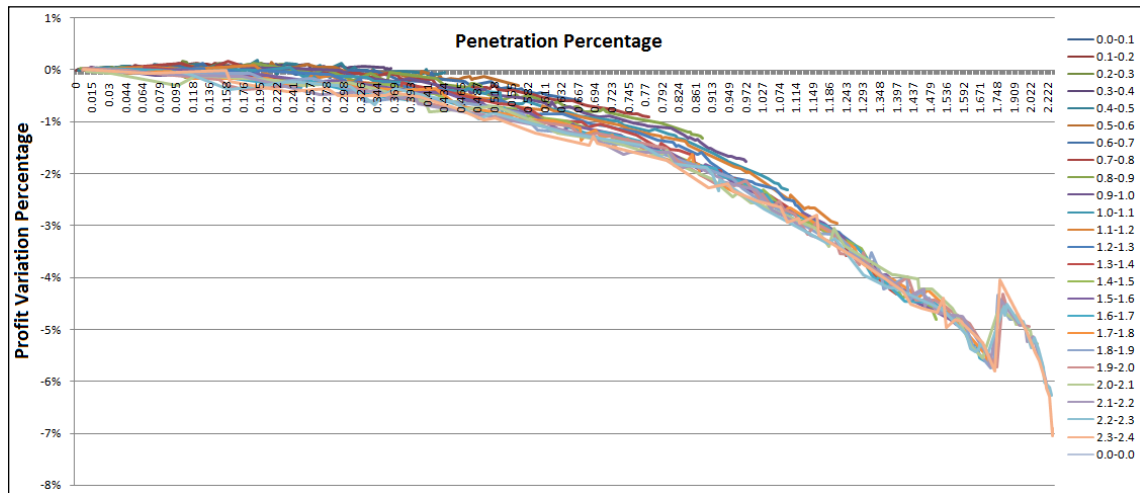


Figure 5-64: BT2 tariff economic operation on the urban feeder with tap changer

Figure 5-64 shows the BT2 tariff scheme under the urban with tap changer case. It can be seen that the same behavior as the non-tap changer case is achieved, descending profit variation curves with small spread between the behavior interval curves. The largest profit loss achieved was 7 % for a 222 % penetration percentage scenario.

The discontinuity on the curves that exist at the 170 % penetration mark is produced by a jump in capacity related investment in conductors, which can be seen in Figure 5-65, where the investments in conductors jump from 5.000 US\$ to 15.000 US\$. This increase in investments reduces the operational losses of energy and power during the four year of evaluation of the model, hence, better economic outcomes.

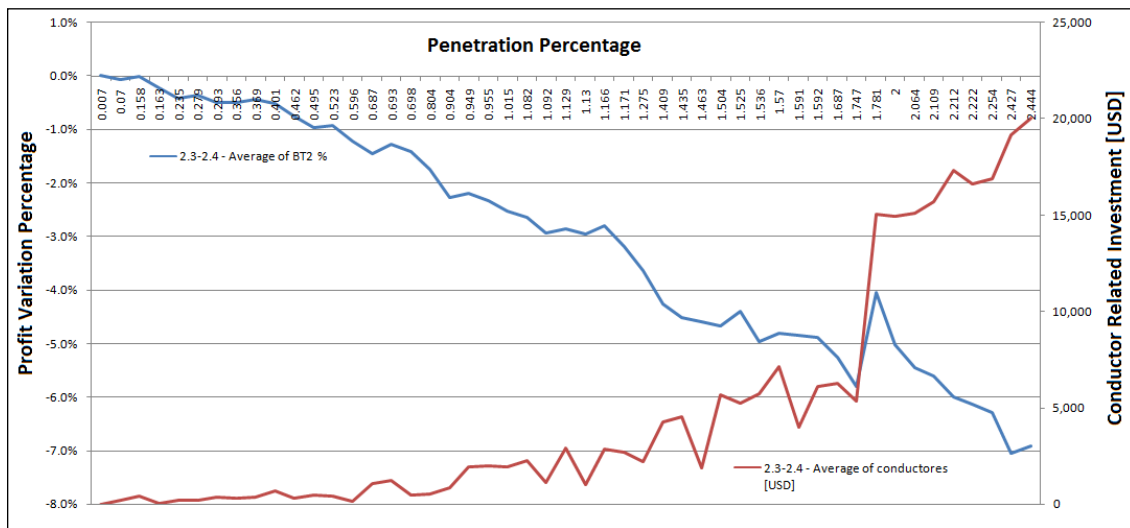


Figure 5-65: BT2 tariff scheme profit variation and conductor related capacity investment

Figure 5-66 shows the profit variation outcome of the proposed BT1* tariff scheme. This tariff presents a similar behavior as the BT2 tariff scheme, with low positive profit variation for low penetration scenarios and negative profit variations for higher penetrations scenarios. Again low spread was detected in comparison with the BT1 tariff, helping to decrease the uncertainty of the future for the DNO company. The discontinuity can be seen again at the 170 % penetration mark. The largest profit loss reached a value of almost 6 %, again 1 % less than the BT2 tariff.

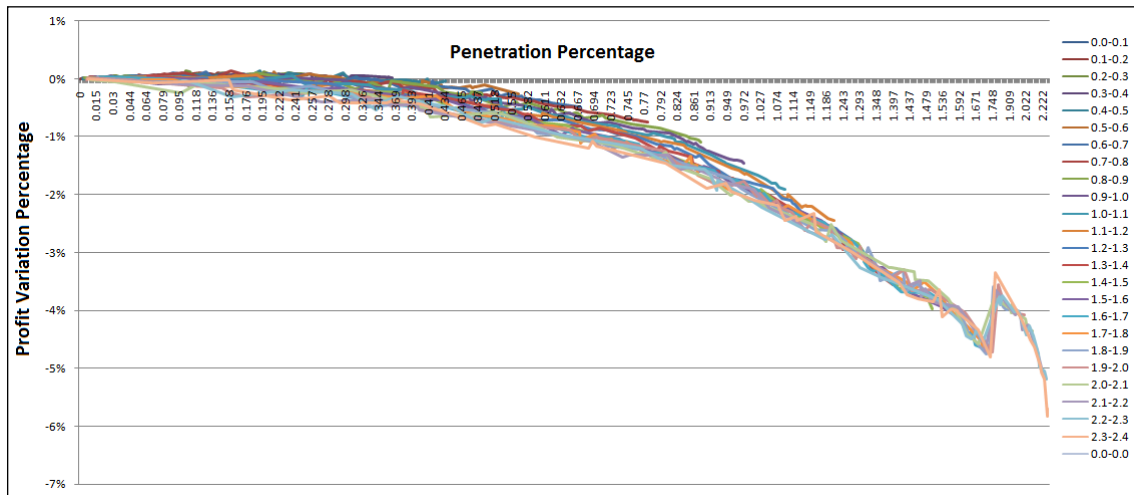


Figure 5-66: BT1* tariff economic operation on the urban feeder with tap changer

5.2.2.2 Rural

In this section the operational results for the rural case are presented.

5.2.2.2.1 No Tap Changer

Figure 5-67 shows the four year operational outcome for the rural feeder without tap changer: under the BT1 tariff scheme:

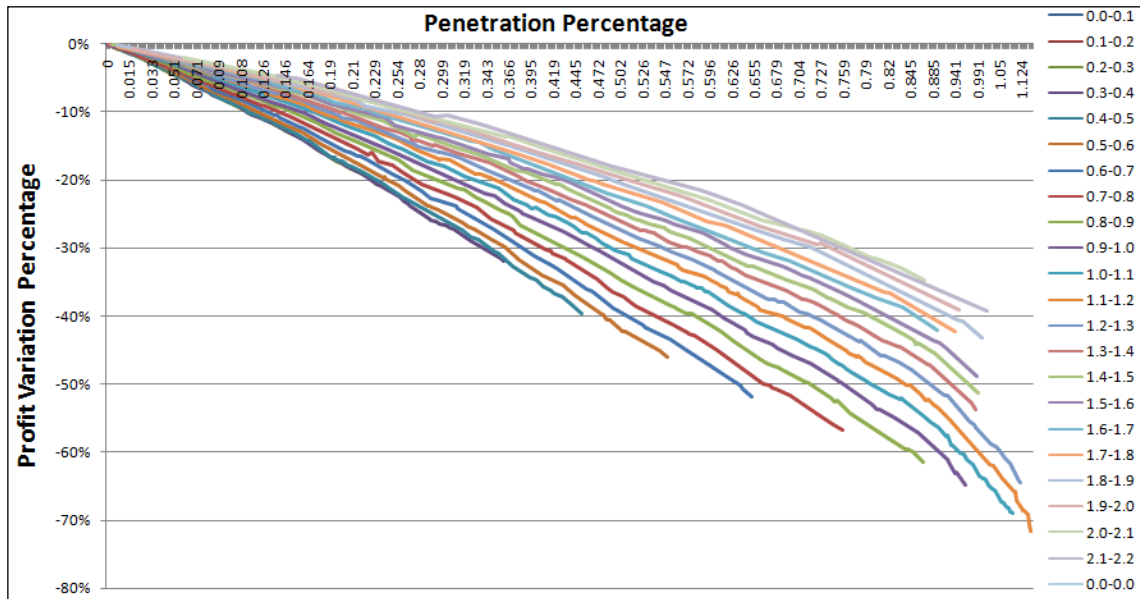


Figure 5-67: BT1 tariff economic operation on the Rural Feeder without Tap Changer

The rural feeder, using the BT1 tariff, presents the same trend as the urban case with the same tariff, with the exception that no capacity related investments were made. This means that no decreasing energy and power losses appear for high penetration scenarios of DG, hence no positive slope are detected on the profit variation curves, under any behavior interval scenario. Yet again, under the same penetration percentage, the impact is lower for higher concentrations of installed DG; this means fewer clients installing more rooftop PV power impacts less than more clients installing less. No high penetration scenarios were achieved because of the overvoltage problems that the rural feeder with no tap changer presents, leaving no margin for the curves to present positive differential profit slopes or changes for high penetration scenarios. The biggest profit change was held for the 1.1-1.2 p.u. interval with a -71.5 % of variation in comparison with the base case at a penetration mark of 117 %. The BT2 tariff results are shown in Figure 5-68:

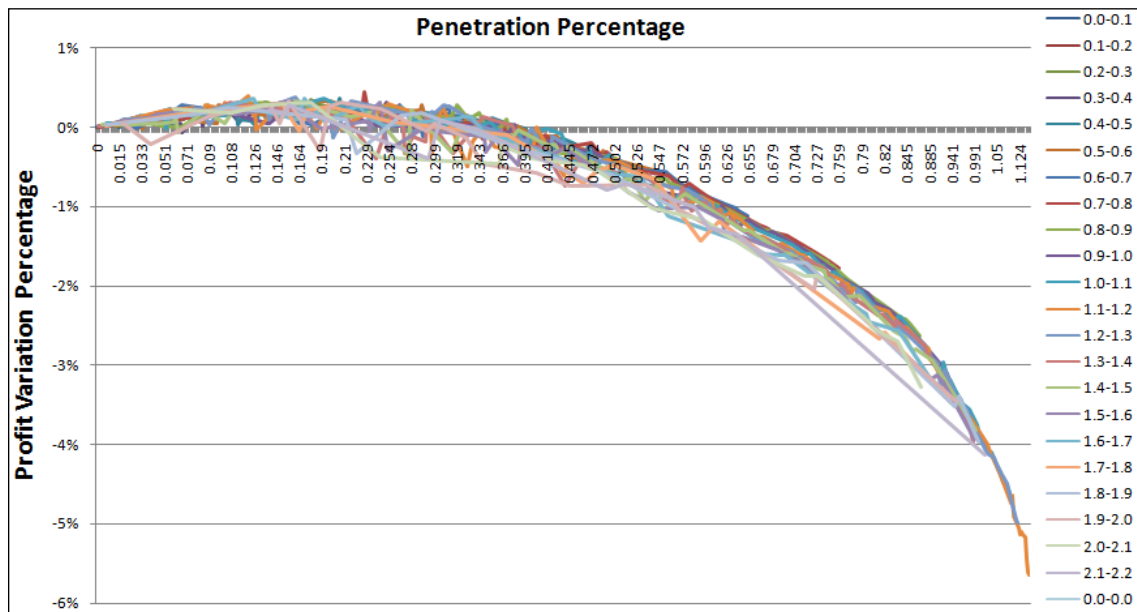


Figure 5-68: BT2 tariff economic operation on the rural feeder without tap changer

The BT2 tariff presents similar curves as the urban case, slightly positive profit variation for low penetration scenarios (under 40 %), followed by negative profit variations for any scenario over that penetration mark. The biggest profit loss was obtained again at the 1.1-1.2 behavior interval with a value of -5.6 % at a penetration mark of 117 %. Again BT2 tariff decreases the impact of DG, because of the fixed charge of capacity and network costs, but still there is a gap to be filled in order to create incentives for the distributed system operator to think of DG as an opportunity rather than a threat.

The results under the proposed BT1* tariff are shown in Figure 5-69:

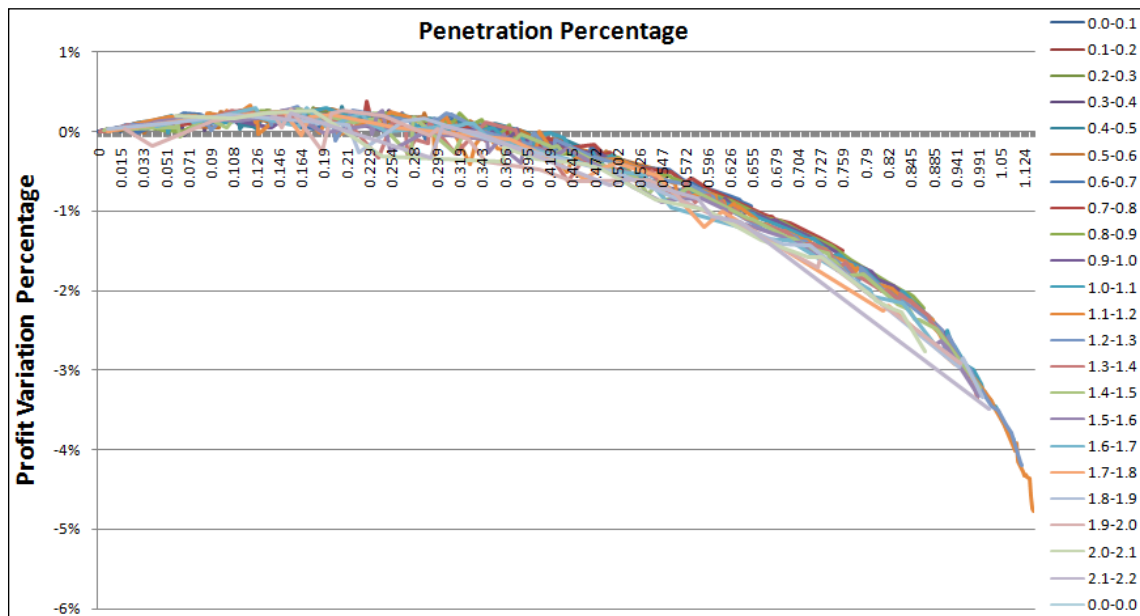


Figure 5-69: BT1* tariff economic operation on the rural feeder without tap changer

The proposed tariff presents a similar behavior as the BT2 scheme, having low profit gains for low penetration scenarios followed by profit losses for high penetration scenarios. In this case the maximum profit loss was smaller than the BT2 tariff scheme, reaching a value of -4.7 % for the behavior interval 1.1-1.2 and a penetration of 117 %.

5.2.2.2.2 With Tap Changer

The rural case with tap changer allows more penetration scenarios to be feasible. Yet again we can see that for both the BT1 and BT2 tariff schemes the distribution company presents profit losses. For all the analyzed scenarios, under the BT1 (Figure 5-70) scheme, the distribution company perceives negative profit variations for every penetration scenario, behaving similarly to the urban case with tap changer, presenting a spread of the profit variation curves depending on the behavior interval scenario, which tells us that for the same penetration percentage, fewer clients installing more PV DG

affects less the profits of the DNO's than more clients installing less PV DG. Meanwhile the BT2 scheme (Figure 5-71) allows small positive profit variations (0.35 %) to be achieved for low penetration scenarios, while only negative profit variations were achieved for higher penetration scenarios, achieving a maximum profit loss of 19 % for an extreme penetration scenario of 185 %. The proposed BT1* tariff (Figure 5-72) shows a similar behavior in comparison with the BT2 tariff scheme, small positive profit variations for low penetrations scenarios and negative profit variations for larger penetration scenarios, achieving a maximum profit loss of 16 %.

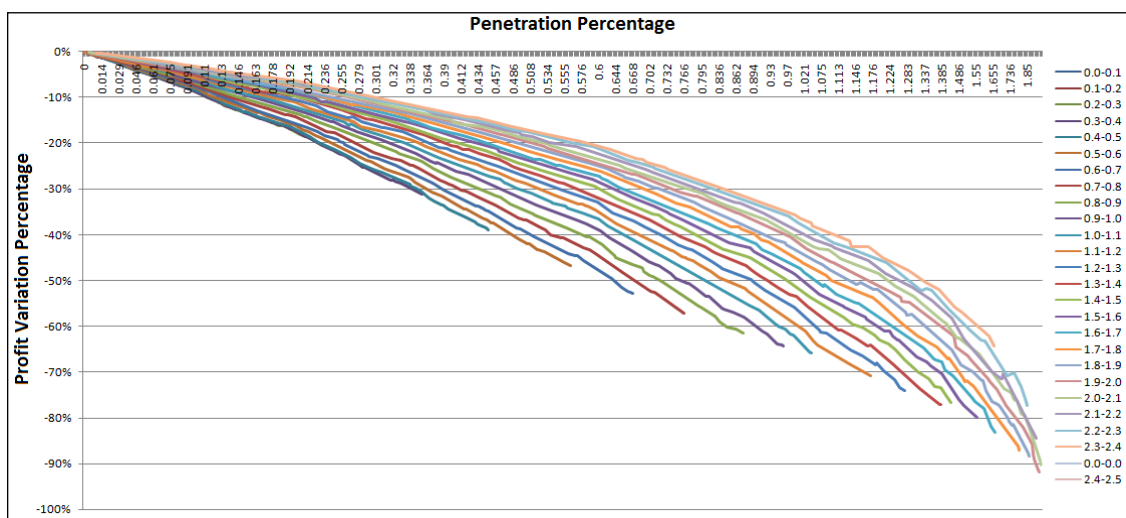


Figure 5-70: BT1 tariff economic operation on the rural feeder with tap changer

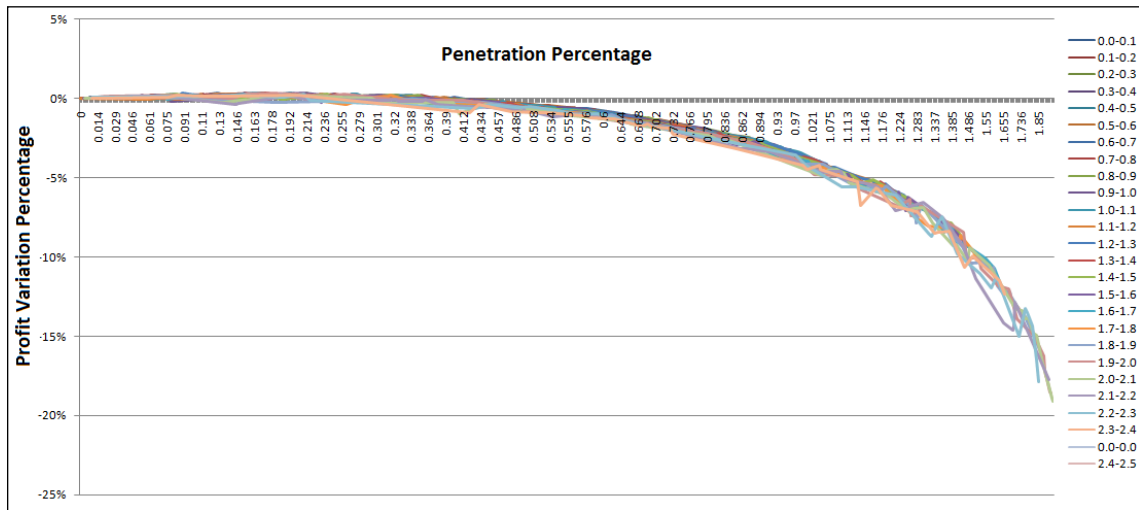


Figure 5-71: BT2 tariff economic operation on the rural feeder with tap changer

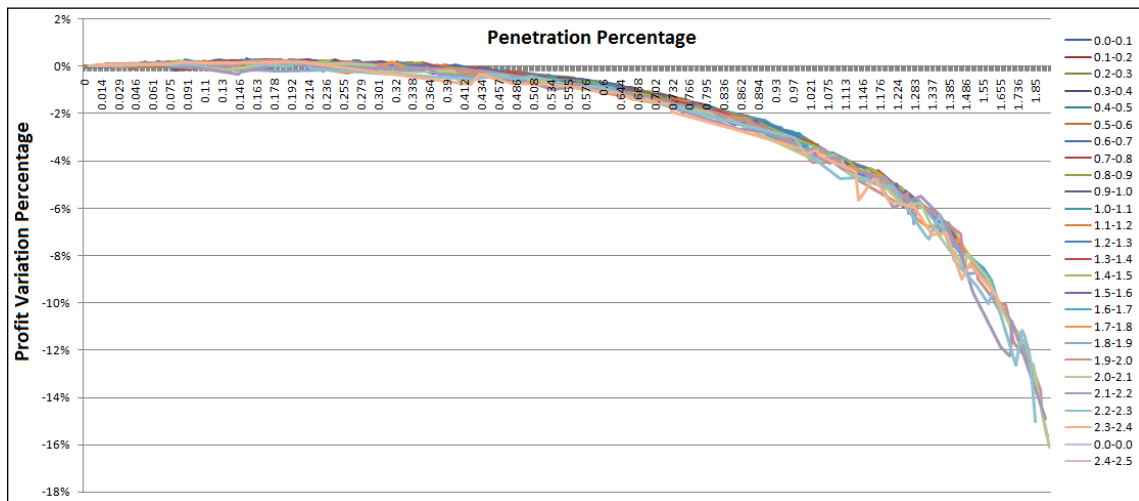


Figure 5-72: BT1* tariff economic operation on the rural feeder with tap changer

5.2.2.3 Socializing the Incremental Costs

This section analyses the exercise of charging the regulated clients for the added cost magnitude that PV DG brings to the system, calculating the socialized cost of a MWh of energy that would give as a result a DNO's profit change as invariant as possible, relative to the base case without DG. Table 5-10 presents the socialized incremental costs of energy using a stepped cost scheme that minimizes the quadratic difference of

the profits between the base case and all the penetration scenarios, calculated for the T2, T1 and T2 BASA tariff schemes. This incremental cost scheme is mentioned in [5]. The stepped added cost function works as a solution to adjust to the non-linear behavior of the incremental costs produced by DG relative to the penetration percentage that this three tariff schemes have, calculating for every penetration interval a cost per consumed MWh in order to keep the DNO's profit variations close to zero under any penetration scenario. For penetration scenarios under the 50 % penetration mark no socialized cost is needed due to the benefits that low penetrations of DG bring to the system. Passed this point, the costs start to increase reaching values of 1.3 and 4.5 US\$/MWh for the Urban and Rural case respectively under the T2 tariff scheme. T1 and T2 BASA tariff schemes need less added cost in order to lower profit decrease, reaching maximum values of 0.9 and 3.0 US\$/MWh for the Urban and Rural case respectively. This exercise shows again the better performance of BASA tariffs.

Table 5-10: Socialized incremental cost of energy for the different tariff schemes.

Socialized Incremental Costs of DG [US\$/MWh]	Penetration Step %	T2	T1 BASA	T2 BASA
Urban	25	0.0	0.0	0.0
	50	0.0	0.0	0.0
	75	0.2	0.2	0.2
	100	0.4	0.3	0.3
	125	0.7	0.5	0.5
	150	1.1	0.8	0.8
	175	1.4	1.0	1.0
	200	1.3	0.9	0.9
Rural	25	0.0	0.0	0.0
	50	0.0	0.0	0.0
	75	0.3	0.2	0.2
	100	0.7	0.5	0.5
	125	1.3	1.0	1.0
	150	2.1	1.5	1.5
	175	3.3	2.2	2.2
	200	4.5	3.0	3.0

5.2.2.4 Average Energy Losses Expansion Factor

The use of an average energy losses expansion factor (AELEF) that considers the complete daily operation of a distribution feeder overestimates the losses during the day time, where energy losses are lower than the average that considers peak demand energy losses. Table 5-11 illustrates the profit losses using the T2, T1 and T2 BASA tariff schemes that do not recognize avoided losses as part of the payment's done to the DG owners. The lack of avoided energy losses payment (unitary AELEF) decreases the profit losses perceived under all tariff schemes. The BASA tariffs presented an increase in profits for a large percentage of the analyzed scenarios at the urban feeder, being the T1 and T2 BASA tariffs the ones with better performance (lower added costs). The T1 BASA kept the profit variation closer to zero, while the T2 BASA presented higher

profit gains. The rural feeder presents profit gains for penetrations lower than 100 % under the BASA tariff schemes. For larger penetration scenarios, losses reached up to 5.9 and 7 % for the T1 and T2 BASA tariff schemes respectively. The T2 tariff presented the lowest performance of the three analyzed tariffs.

Table 5-11: Profit losses vs. penetration % without avoided energy loss payment

% Profit Loss		T2		T1 BASA		T2 BASA	
Feeder	Penetration %	Min	Max	Min	Max	Min	Max
Urban	25	-0.3	0.0	-0.8	-0.3	-0.9	-0.3
	50	-0.3	0.2	-1.2	-0.5	-1.4	-0.6
	100	0.4	1.0	-1.1	-0.5	-1.3	-1.3
	150	1.4	2.7	-0.4	0.1	-0.5	0.1
	200	1.0	1.4	-1.1	-0.9	-1.4	-1.1
Rural	25	-1.1	-0.1	-1.6	-1.0	-2.0	-1.2
	50	-1.4	0.3	-2.3	-1.7	-2.7	-2.0
	100	0.0	2.0	-2.1	-1.1	-2.5	-1.3
	150	4.2	5.9	0.4	-2.0	-0.5	2.3
	200	10.6	12.0	5.0	-5.9	5.9	7.0

5.3 Analysis

After analyzing both urban and rural cases with and without tap changer at the feeder's header, different effects were seen varying from technical impact of voltages to the economic impact of the operation of the distribution company. This section will discuss these two elements of the impact of DG.

5.3.1 Technical Impact

Technical impacts can be divided in two main groups, voltage and thermal capacity. This section analyzes both.

5.3.1.1 Voltage

DG penetration impacts voltages on every analyzed case, increasing the magnitude of the voltage profiles by decreasing the current that flows from the feeder's header to the loads that install rooftop PV panels. In some cases, when high DG penetration is achieved, the active power flow reverses, flowing from the consumer in direction to the feeder's header. This creates a voltage rise on the nodes close to the generation point.

When consumption near zones with elevated amount of generation is low, the probability of overvoltage rises because of the magnitude of the reversed currents.

The minimum penetration values that trigger overvoltages are summed up in Table5-12. This table helps us understanding how the interactions of DG penetration and voltage work, creating a good tool for regulative exercises for this matter and how to approach it in a secure way.

Table5-12: Minimum penetration values that trigger overvoltages on the analyzed cases

Tap Changer	Behavior Interval	Urban	Rural
Without	Min	1.7-1.8 167.0%	1.2-1.3 119.0%
	Max	2.3-2.4 34.0%	2.1-2.2 10.2%
With	Min	- -	2.2-2.3 225.0%
	Max	- -	2.3-2.4 188.0%

5.3.1.2 Thermal Capacity

The penetration of DG implies injections of active power in different points of the feeder that, under certain circumstances, produce reverse active power flows that converge in certain branches of the system where thermal capacity violations can be triggered. These branches can be distribution lines at low or medium voltage or low voltage transformers and need to be replaced in order to ensure the security of operation of the system.

For both with and without tap changer urban cases, and analyzing behavior intervals over 1.4-1.5, penetrations as low as 1 % can trigger thermal capacity violations. Under that behavior interval threshold no capacity related investments are required. This gives us a hint that by controlling the amount of power that clients are able to install in relationship to their design load size, the thermal capacity problems could be minimized. For the rural case without tap changer no capacity related investments were needed because no high penetration scenarios were feasible due to overvoltage problems. The lowest penetration that caused overvoltages was 10.2 % (see table 5). In contrast, the rural case with tap changer triggered capacity related investments for behavior intervals 1.6-1.7 and higher at a penetration level of 51.9 % and triggered overvoltages at a minimum penetration of 188 %. The summarized values of minimum penetrations that triggered capacity related investment are shown in Table 5-13:

Table 5-13: Minimum penetration values that trigger capacity related investment for the analyzed cases

Tap Changer	Behavior Interval	Urban	Rural
Without	Min	1.5-1.6 167.0%	- -
	Max	2.3-2.4 0.9%	- -
With	Min	1.4-1.5 100.2%	1.6-1.7 153.3%
	Max	2.3-2.4 1.6%	2.3-2.4 51.9%

5.3.1.3 Aggregated Technical Impact

When both, voltage and thermal capacity impacts are analyzed together we can modify the range of DG penetration and behavior intervals where no voltage violations are triggered and no capacity related investments are made. Table 5-14 shows the value of the merged impacts.

Table 5-14: Summarized technical thresholds of voltage violations and capacity related investments

Tap Changer	Behavior Interval	Urban	Rural
Without	Min	1.5-1.6 2.7%	1.2-1.3 119.0%
	Max	2.3-2.4 0.9%	2.1-2.2 10.2%
With	Min	1.4-1.5 100.2%	1.6-1.7 154.0%
	Max	2.3-2.4 1.6%	2.3-2.4 51.9%

5.3.2 Economic Impact

The analyzed data of the operational model showed that for all the analyzed scenarios the distribution company perceived profit losses under the BT1 tariff scheme, while for the BT2 and BT1* tariff schemes, low profit gains (<1 %) are achieved for low penetration scenarios, and profit loss are achieved for larger penetration scenarios.

Apart from profit variation relative to the penetration percentage of DG there are other variables that are really important to analyze, such as energy losses and energy consumption from the clients, and how these two affect the profit of the company. A good regulation is the one that captures and maximizes the good externalities of the actors (DER) in the system and minimizes the bad ones. In this section two concepts will be specifically analyzed, net present energy losses and net present consumed energy vs. variation of profit during the four year operation.

5.3.2.1 Energy Losses vs. Profits

Intuitively, less energy losses on an electric distribution system would mean a better economic outcome, but when analyzing the data of the operation under the current regulatory schemes, these are not the results. Figure 5-73 shows how, under the BT1 tariff scheme, lower energy losses do not product a better operational outcome (positive sloped curves). Some behavior interval present negative slopes on some portions of the curves, which are due the fact that higher penetration scenarios come in hand with higher operational energy losses and also DNO perceive higher profit losses on this scenarios, thus the negative sloped curves. Figure 5-74 presents the exercise under the BT2 tariff scheme, showing negative sloped curves on the positive side of the horizontal axis of profit variation percentage. This portion of the curve tells us that even though the DNO are buying and selling less energy, the existence of low penetration of DG helps lowering operational losses and increasing the overall economic performance of the operation. The negative side of the horizontal axis presents the higher penetration scenarios, where lower operational energy losses exist, but they do not drive the profits up anymore. The payments done to DG owners for their surplus energy injected back to the grid increases the costs of operation, lowering the profits relative to the base case. Similar behavior is encountered when analyzing the proposed BT1* tariff scheme (Figure 5-75) with the exception that lower profit losses are achieved at high penetration scenarios.

Figure 5-76, Figure 5-77 and Figure 5-78 present the same exercise for the urban feeder with tap changer, where similar outcomes as the urban case can be seen.

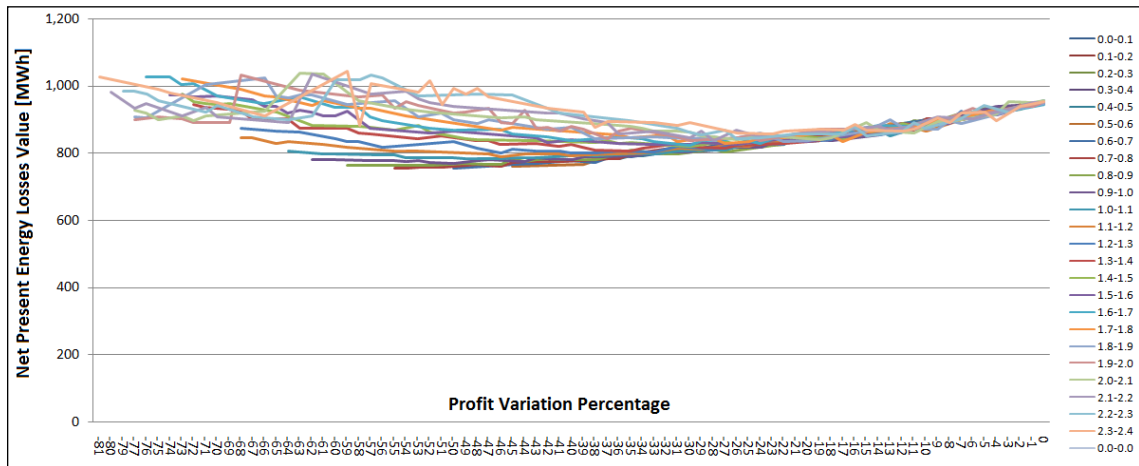


Figure 5-73: Profit variation percentage vs. net present energy losses for the urban case with tap changer under the BT1 tariff scheme

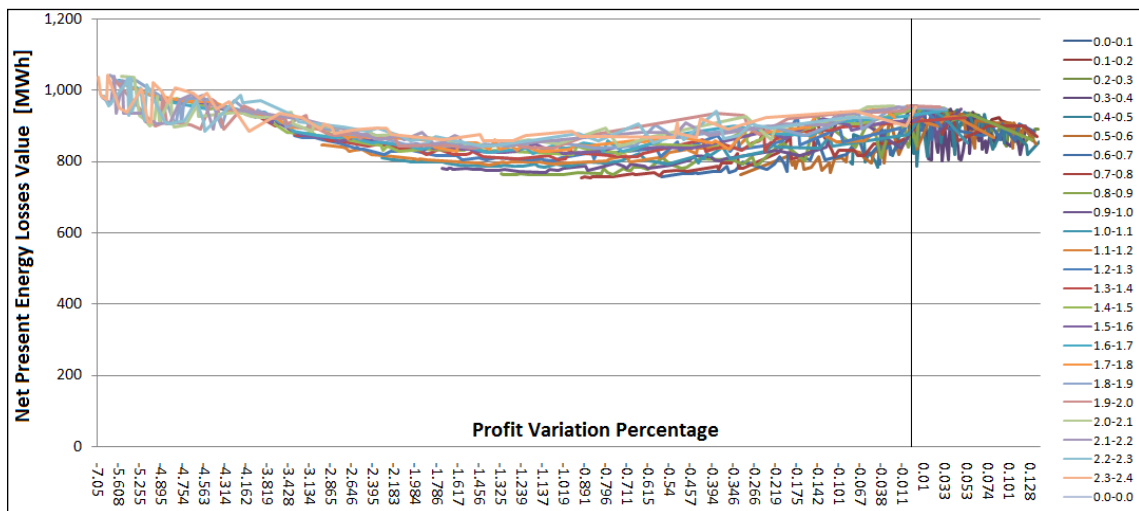


Figure 5-74: Profit variation percentage vs. net present energy losses for the urban case with tap changer under the BT2 tariff scheme

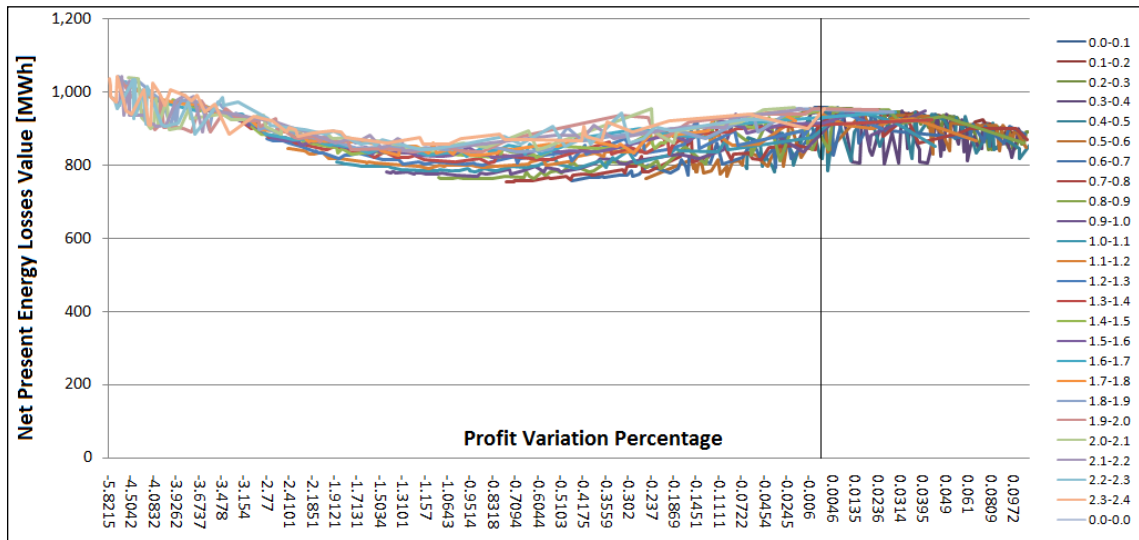


Figure 5-75: Profit variation percentage vs. net present energy losses for the urban case with tap changer under the proposed BT1* tariff scheme

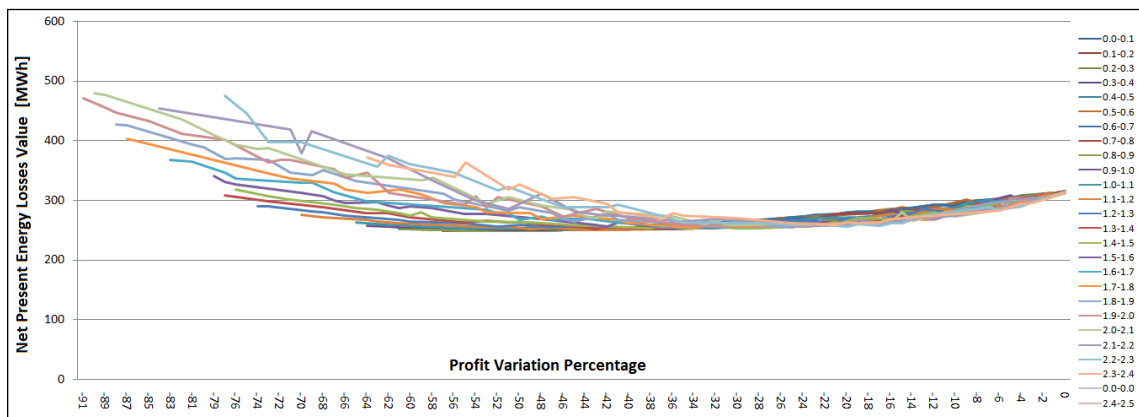


Figure 5-76: Profit variation percentage vs. the net present energy losses for the rural case with tap changer under the BT1 tariff scheme

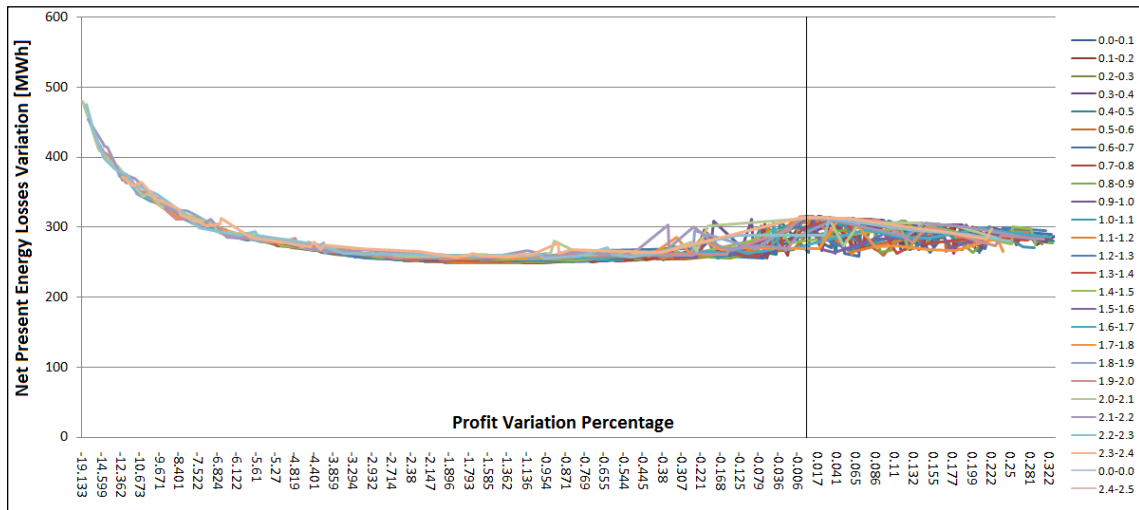


Figure 5-77: Profit variation percentage vs. the net present energy losses for the rural case with tap changer under the BT2 tariff scheme

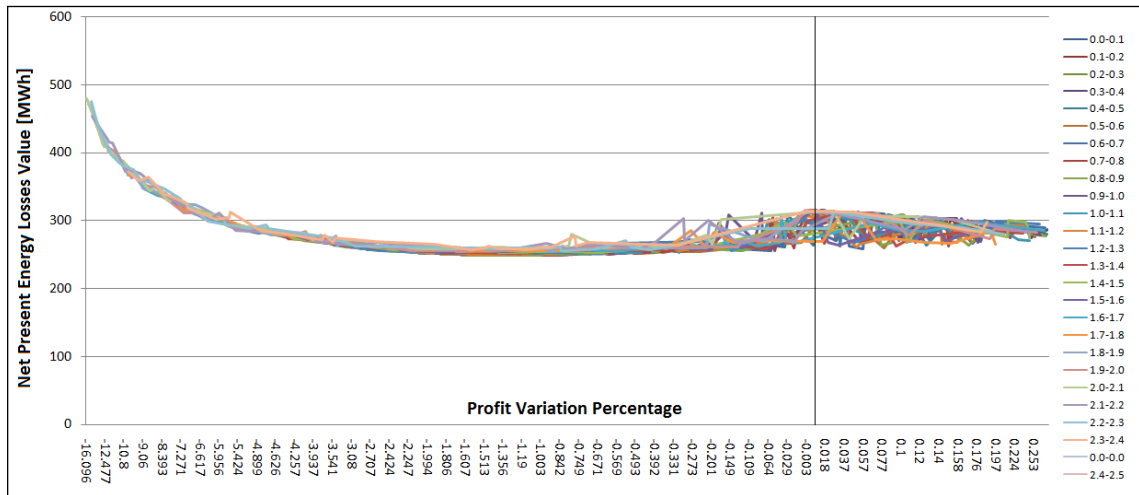


Figure 5-78: Profit variation percentage vs. the net present energy losses for the rural case with tap changer under the proposed BT1* tariff scheme

5.3.2.2 Consumption vs. Profits

Consumption is an important driver of the economic operation of the distribution companies. In 2005, 97 % of the clients of Chilectra had energized tariffs, meaning that any abrupt variation in consumption could cause a change on the economic operation outcome. These changes could be a near future problem and one example of it is the per capita electric energy consumption in the United States, which has stagnated (Figure 5-79) and when PV DG penetration is added, loss of profits are expected if no regulatory changes are done.

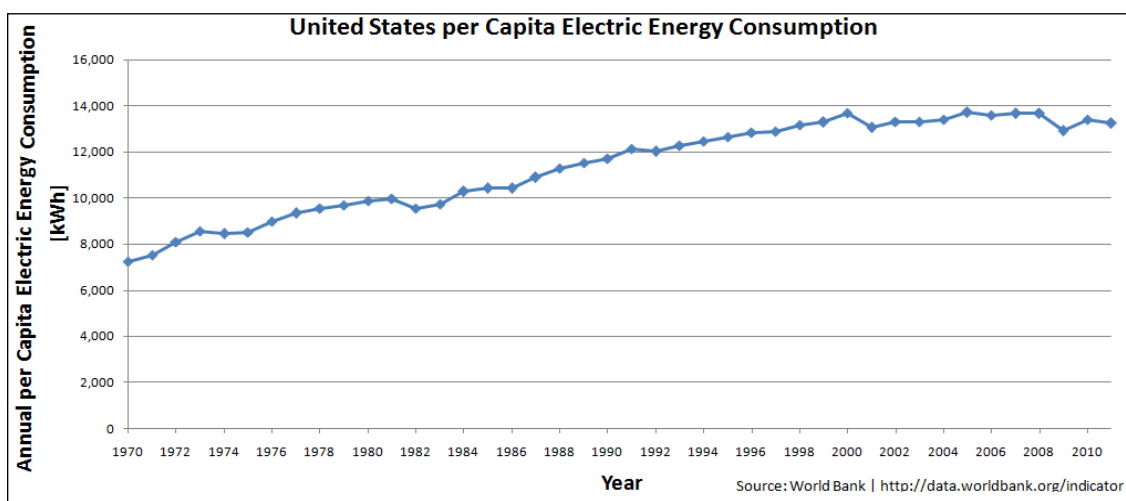


Figure 5-79: United States per capita electric energy consumption

The profit variation data of the economic operation was crossed with the net present energy consumption value of the clients of each feeder, giving as results the dynamics of the actual tariffs under the phenomenon of decreasing consumption by penetration of PV DG. The urban feeder with tap changer presented, under the BT1, BT2 and BT1* tariffs, lower profits for most of the penetration scenarios (BT2 and BT1* presented small

positive profit variations for low penetration scenarios). When crossing this data with the net present energy consumption the BT1 tariff presents an almost perfect linear relationship between consumption and profit variation (Figure 5-80) which tells us that every kWh that stops being consumed by means of PV DG affects the outcome of profits of the enterprise. The same exercise done with the BT2 and BT1* tariff scheme where for some penetration scenarios under 38 % present negative sloped curves, which means that lower consumption of energy is not directly related to lower profits. After the 38+ % threshold of DG penetration the curves of variation of profits vs. consumed energy present only positive slope, which means that when the consumption decreases, so do the profits. This trend is present on every behavior interval and all of them present the same rate of decrease in profits relative to the rate of decrease in consumption. BT2 and BT1* tariff schemes present a similar behavior, yet the second presents a lower relationship between consumption and profits which could help decoupling the consumption with profits.

Figure 5-83, Figure 5-84 and Figure 5-85 present the same exercise for the rural case with tap changer, presenting similar results as the urban case with tap changer. The BT1 tariff scheme presents an almost perfectly linear relationship between variation of profits and net present energy consumption which behaves exactly as the urban case, this is, less consumption means less profits. For the BT2 and BT1* tariff schemes we encounter again the low penetration effect of negative slopes, which means that less consumption is not translated into lower profits. This is only valid for penetration scenarios under 40 %, for larger penetrations the curves present positive slope which means that fewer consumption decreases profits.

Table 5-15 shows the percentage of variation of profits in terms of the percentage of variation of consumption relative to the base case. This sensitivity index tells us that urban feeders are prone to have a lower impact on profits when consumption is decreased by means of PV DG and also that if no tariff schemes measurements are taken, PV DG could be a major threat on both urban and rural feeders, with a larger negative impact potential on rural feeders.

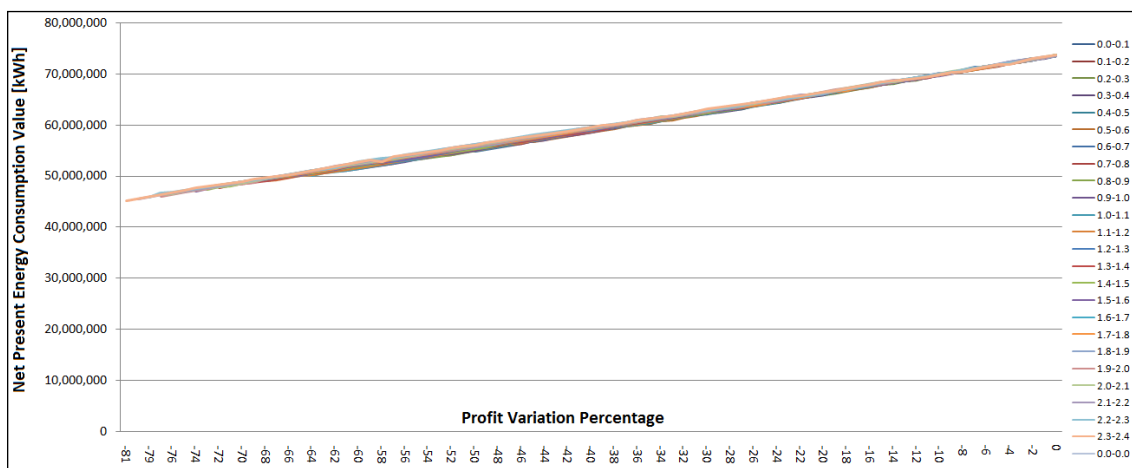


Figure 5-80: Net present consumed energy value vs. profit variation for the urban feeder with tap changer under the BT1 tariff scheme

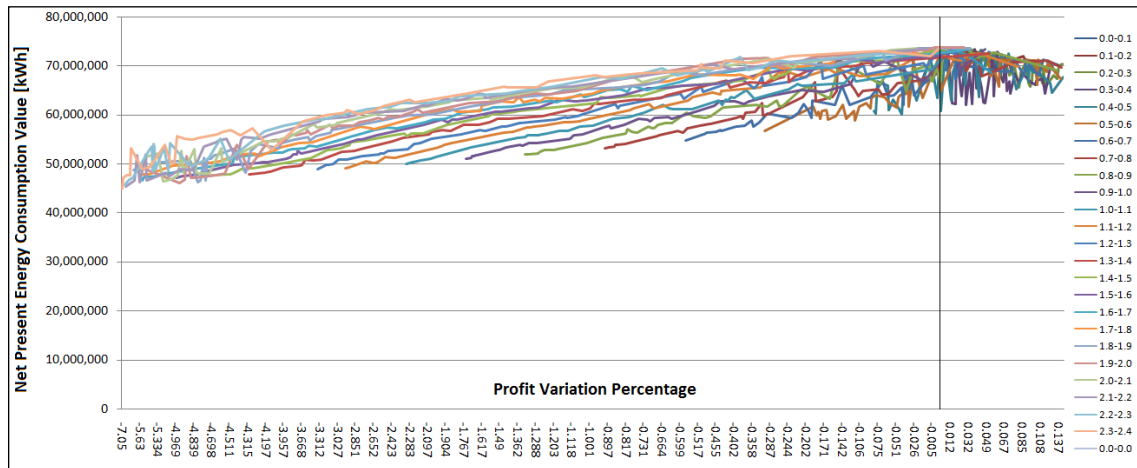


Figure 5-81: Net present consumed energy value vs. profit variation for the urban feeder with tap changer under the BT2 tariff scheme

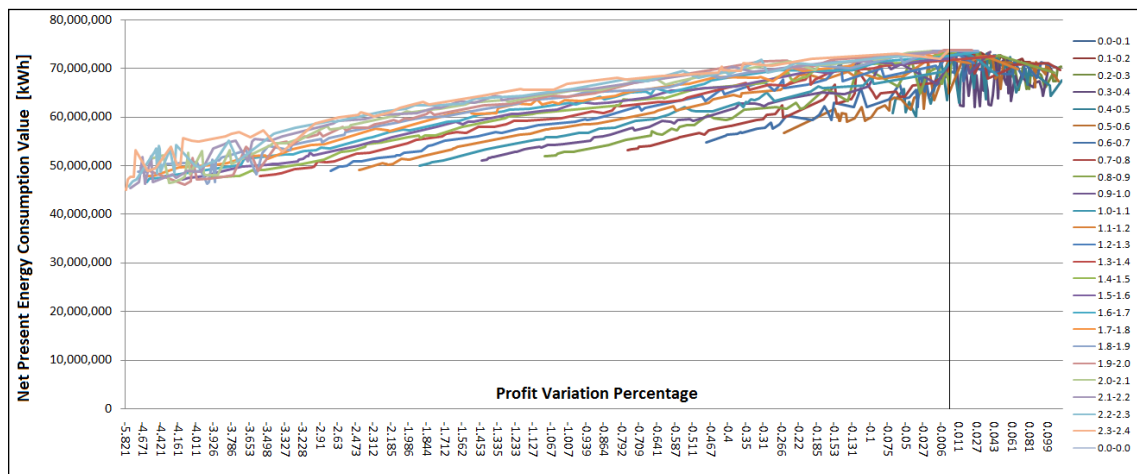


Figure 5-82: Net present consumed energy value vs. profit variation for the urban feeder with tap changer under the proposed BT1*tariff scheme

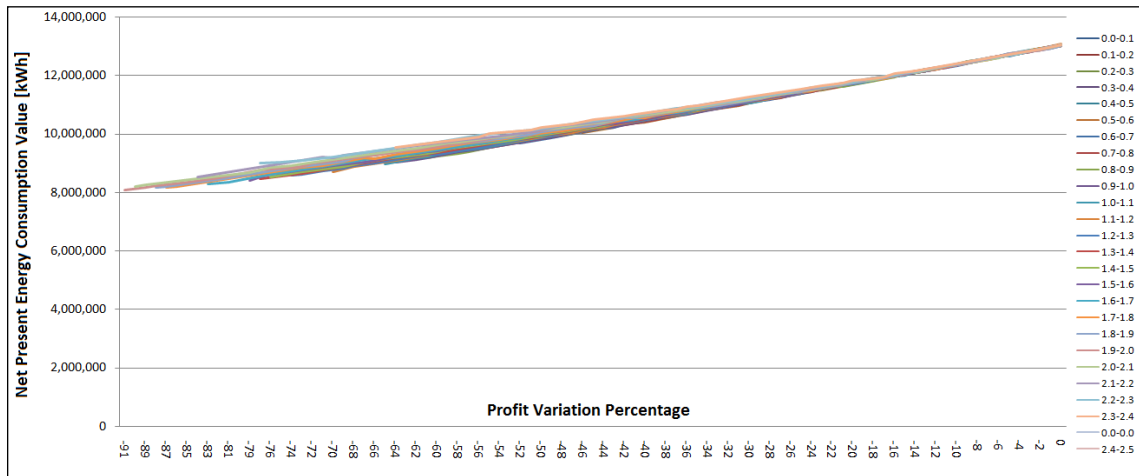


Figure 5-83: Net present consumed energy value vs. profit variation for the rural feeder with tap changer under the BT1 tariff scheme

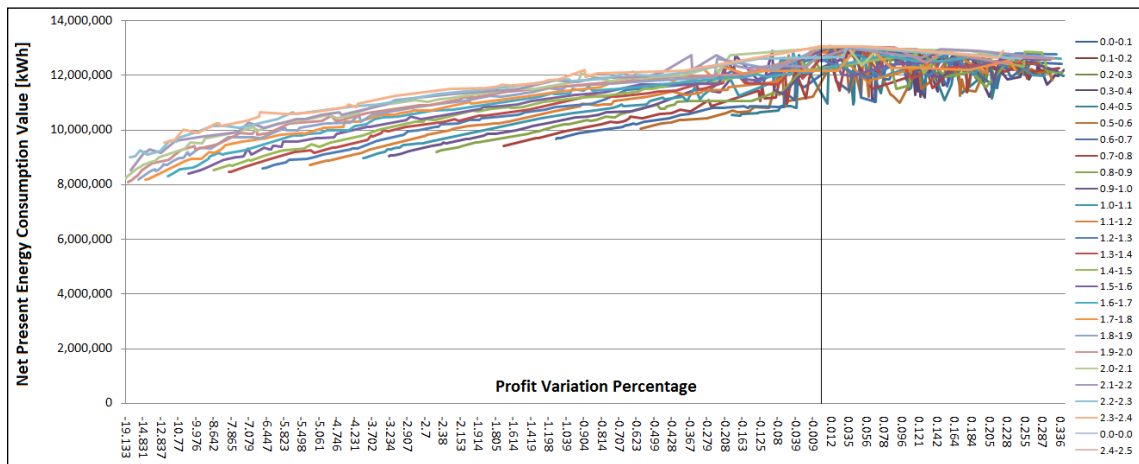


Figure 5-84: Net present consumed energy value vs. profit variation for the rural feeder with tap changer under the BT2 tariff scheme

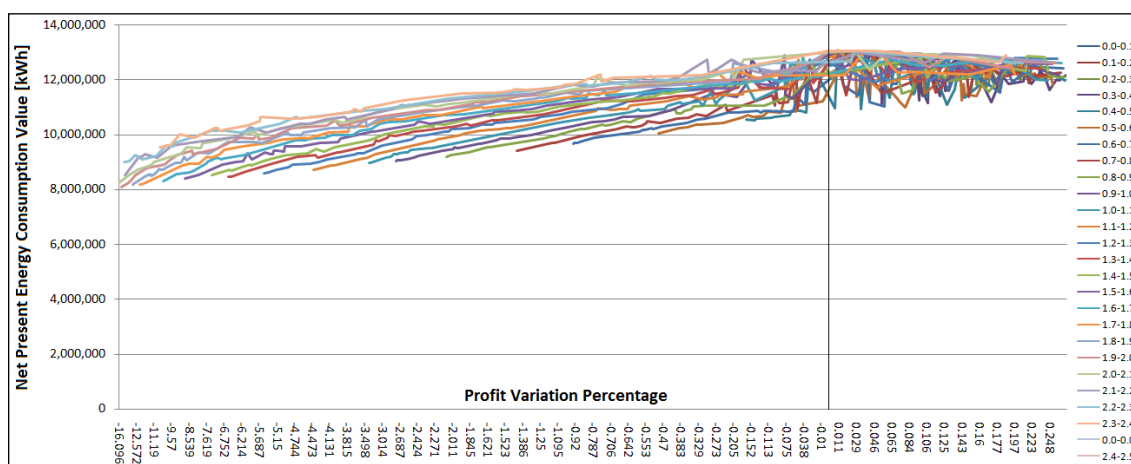


Figure 5-85: Net present consumed energy value vs. profit variation for the rural feeder with tap changer under the proposed BT1 tariff scheme

Table 5-15: Sensitivity index for the analyzed cases based on the superior envelope

Tap Changer	Profit % / kWh %	Urban	Rural
Without	BT1	2.07	-
	BT2	0.18	-
	BT1*	0.15	-
Without	BT1	2.08	2.38
	BT2	0.19	0.57
	BT1*	0.15	0.48

5.3.2.3 Size of load sensitivity analysis

The last section analyzed the penetration scenarios under the assumption that any client could install PV power, independent of its consumption size. In Annex 3, it is demonstrated that, under the current tariff scheme, large clients benefit more from installing PV panels to meet their electric energy needs. This section analyzes the parameterized cases of only allowing the top 10, 20 and 40 % of the largest clients to install PV panels as an effort to understand what would really happen if DG becomes a

trend. The exercise is done under the urban feeder with tap changer feeder. Figure 5-86 presents the percentage variation of profits under the BT1 tariff scheme for five behavior scenarios and the different parameterized size of clients, largest 10, 20 and 40 %. This figure illustrates that under this tariff scheme there is no difference in profit variation between the three parameterized cases, under the assumption of same penetration level and behavior interval. Figure 5-87 presents the same exercise under the BT2 tariff scheme, having as an outcome the exact same result as the BT1 tariff scheme, that is to say, no difference between the client's size cases. This two figures let us understand the factors that really affect the distribution company profits are the amount of installed PV power (penetration) and the per unit relationship of installed capacity vs. size of load for a given penetration value.

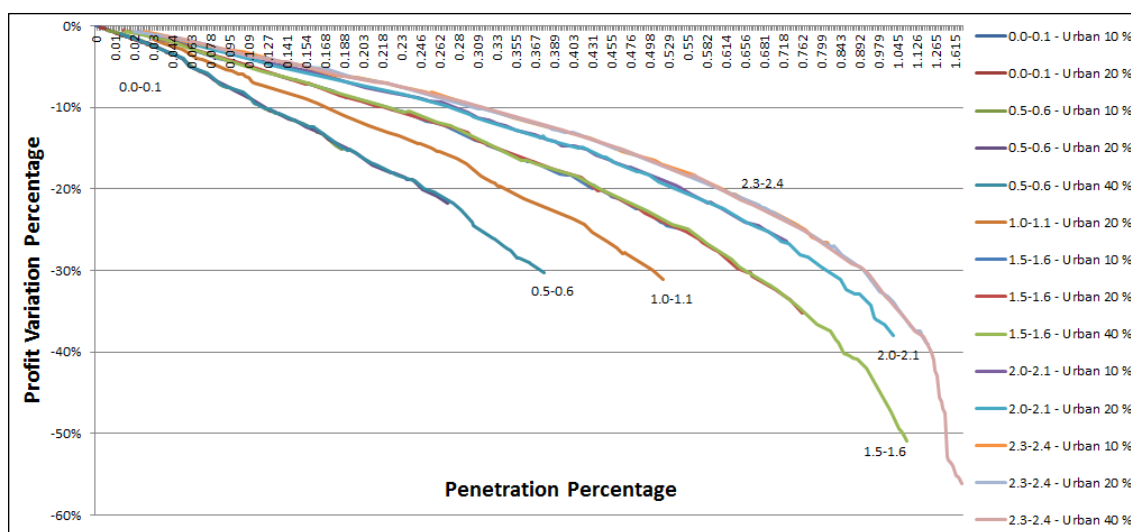


Figure 5-86: Profit variation for the parameterized size of client's analysis under the BT1 tariff scheme

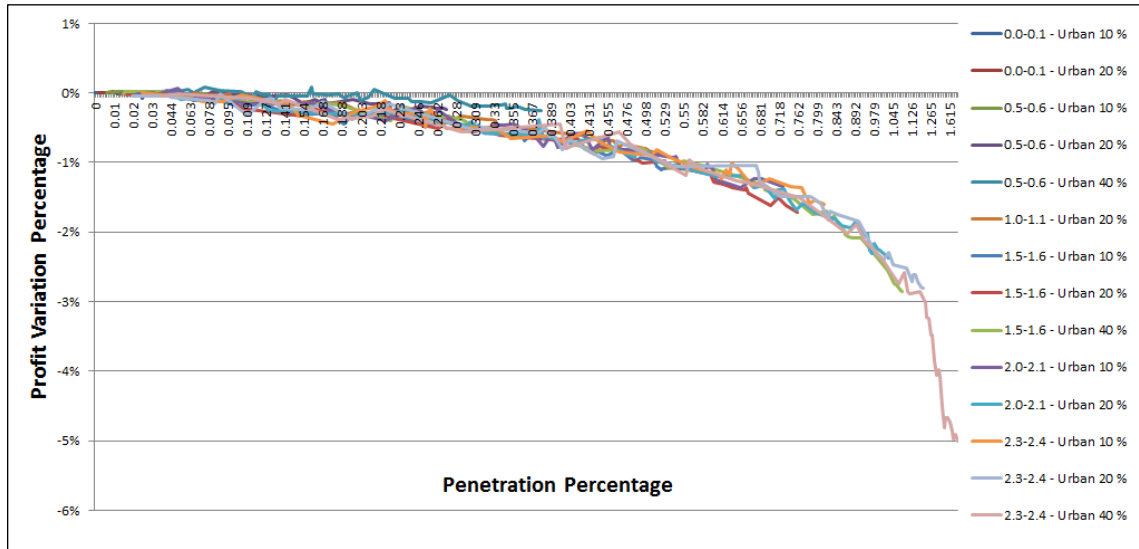


Figure 5-87: Profit variation for the parameterized size of client's analysis under the BT2 tariff scheme

5.3.2.4 Average cost of energy

Under the actual net billing law, the surplus generation of the clients that is injected back to the network must be valued as the energy cost plus the expected avoided losses. Under this assumption the distribution company would have two electric energy sources, the feeder's header, which brings energy from the upstream network and the embedded generators, where the first one has a price P_e and the second one, the same price plus the avoided losses. This section analyzes the impact of the embedded generation at the purchase price of the energy by evaluating the average cost of energy that the distribution company has to pay. All the calculations are made under the urban feeder with tap changer and the hourly average cost of energy was calculated using equation (12):

$$P_{e,average | y,m,h} = \begin{cases} \text{if } p_{y,m,h} > 0 & \frac{p_{y,m,h} \cdot P_e + P_e \cdot El_f \cdot \sum DG_{y,m,h}}{\sum C_{y,m,d}} \\ \text{if } p_{y,m,h} < 0 & \frac{P_e \cdot El_f \cdot \sum DG_{y,m,h}}{\sum C_{y,m,d} - p_{y,m,h}} \end{cases} \quad (12)$$

Where $P_{e,average | y,m,h}$ is the average cost of a kWh for the year y , month m and hour h , $p_{y,m,d}$ the active power at the feeder's header, P_e the energy cost per kWh, El_f the energy expansion loss coefficient, $\sum GD_{y,m,d}$ the sum of the surplus power injected back to the network and $\sum C_{y,m,d}$ the sum of the power consumption of the clients. Figure 5-88 shows the hourly average energy cost for January of the first year of the evaluation horizon for a behavior interval of 100 % (1 p.u.) and a 16.3 % of penetration. When the solar panels start injecting power, the average cost rises right away, because we of the nature of the 1 p.u. behavior interval. From 6 am till 18 pm there is no load that consumes more than what their generators inject, having as a result clients that inject back to the network for the entire portion of the day, obligating the distribution company to pay them the energy fee plus the average avoided losses. Figure 5-89 shows the same exercise for the entire first year of evaluation. During the winter season the amount of power that the panels generate is lower relative to the load, hence there is only a decrease in consumption allowing lower losses to be achieved that translate in a negative variation of average cost of energy. The maximum hourly average energy cost variations was 1.77 %. The same exercise under the 2 p.u. behavior interval and a 32.6 % of penetration, produces higher variations of average energy costs, reaching a maximum of 5 % at 10 am, February, year 1 (Figure 5-90). The yearly resolution, in Figure 5-91, shows the same behavior for the winter season with its singular low increase of hourly energy cost. The maximum and

minimum average energy cost variations for this penetration scenario are 5 % and -0.089 % respectively. Extreme behavior intervals such as a 7 % (114 % of penetration) produces increases in average hourly energy cost up to 7 % (Figure5-92). Low behavior intervals scenarios show that the hourly average energy cost doesn't present negative variations in its value, Figure 5-93 shows how the yearly average energy cost, considering 12 months and 24 hours a day, is an increasing function of the behavior interval (or penetration assuming a non-changing configuration of the embedded generation), thus under the present net metering tariff scheme the distributor doesn't benefit for having generators embedded on the network.

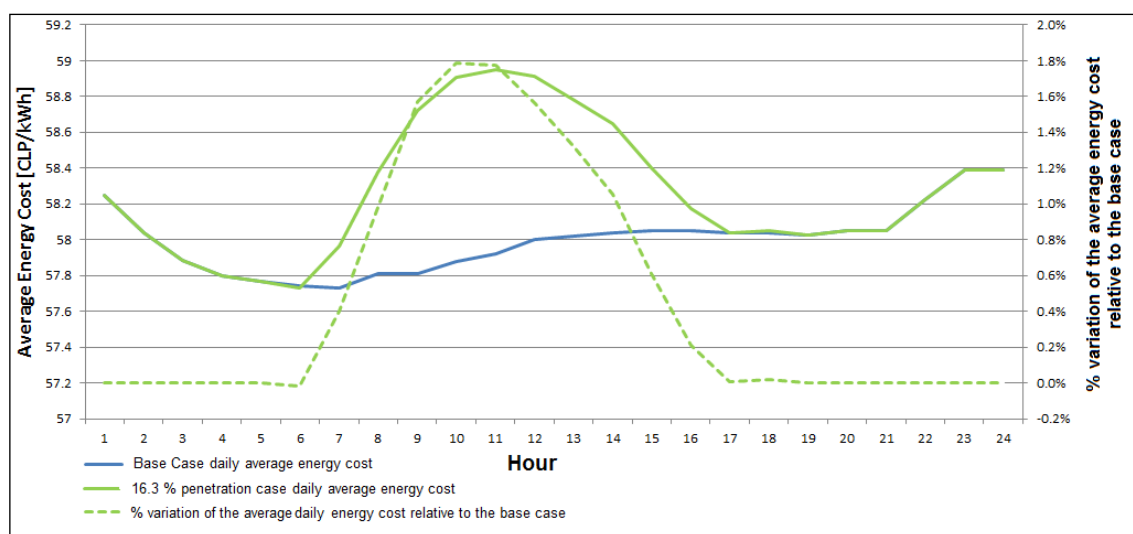


Figure 5-88: Hourly average energy cost comparison for the 1 p.u. behavior interval

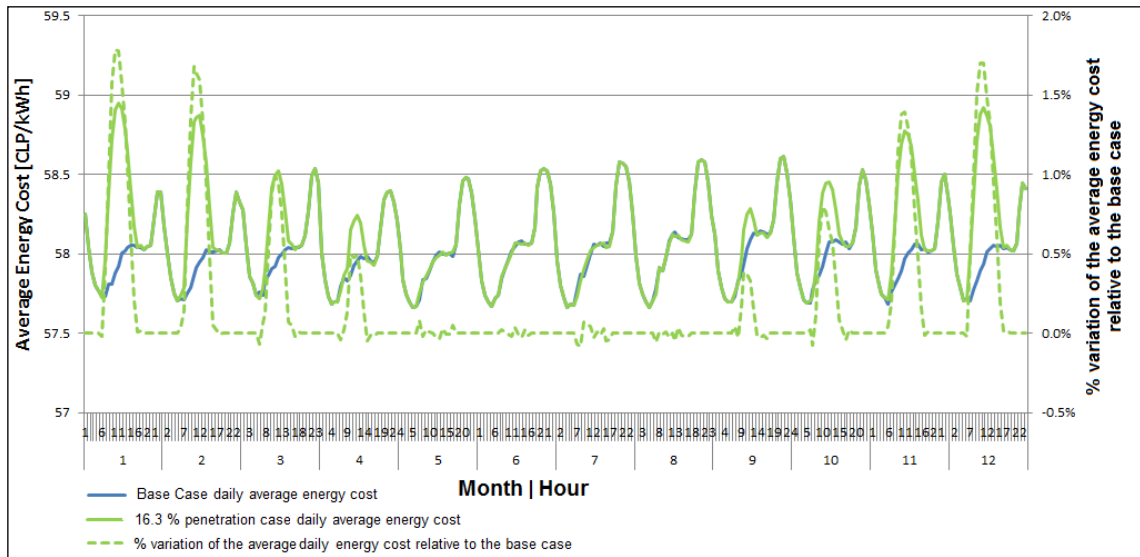


Figure 5-89: Hourly average energy cost comparison for the 1 p.u. behavior interval for the first year of the analysis horizon

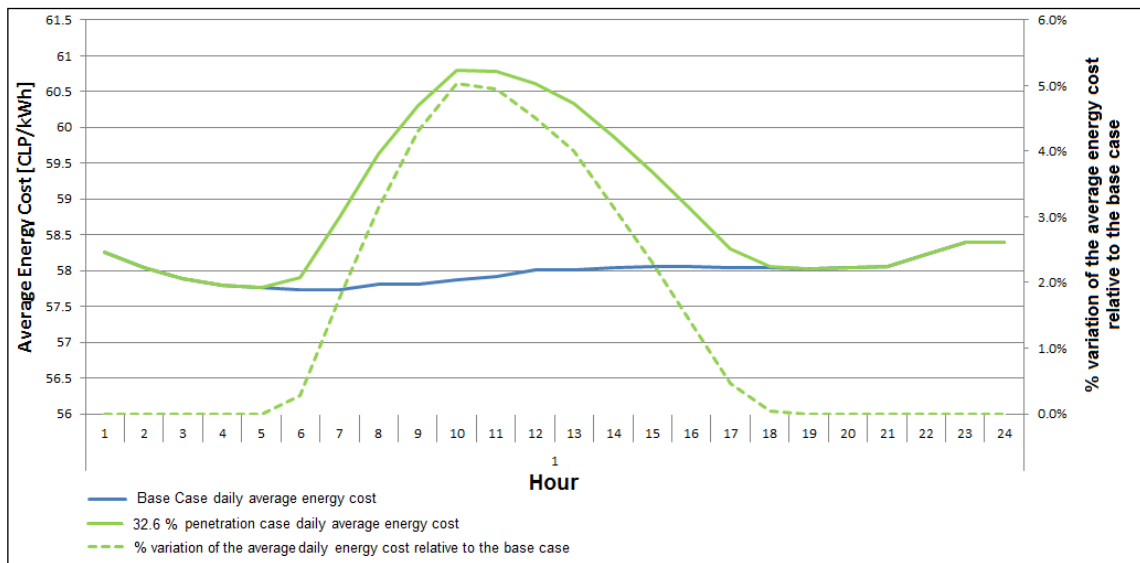


Figure 5-90: Hourly average energy cost comparison for the 2 p.u. behavior interval

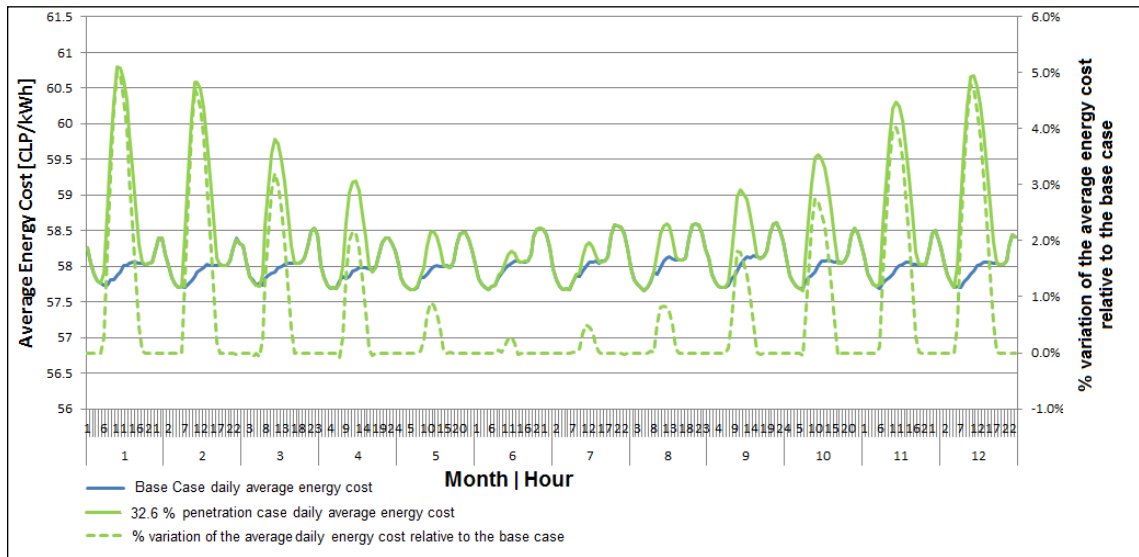


Figure 5-91: Hourly average energy cost comparison for the 2p.u. behavior interval for year 1 of the analysis horizon

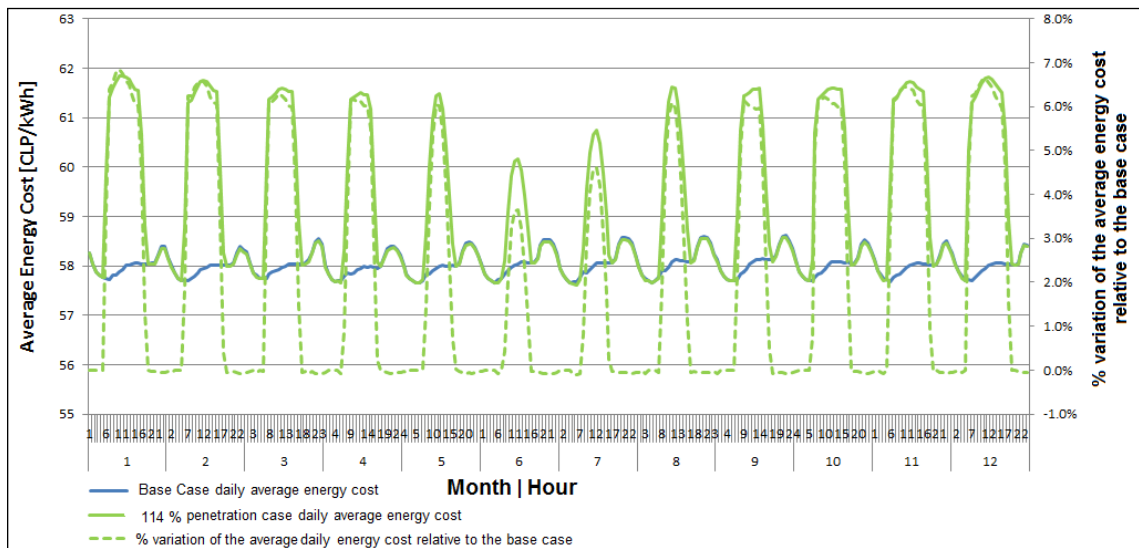


Figure 5-92: Hourly average energy cost comparison for the 7p.u. behavior interval for year 1 of the analysis horizon

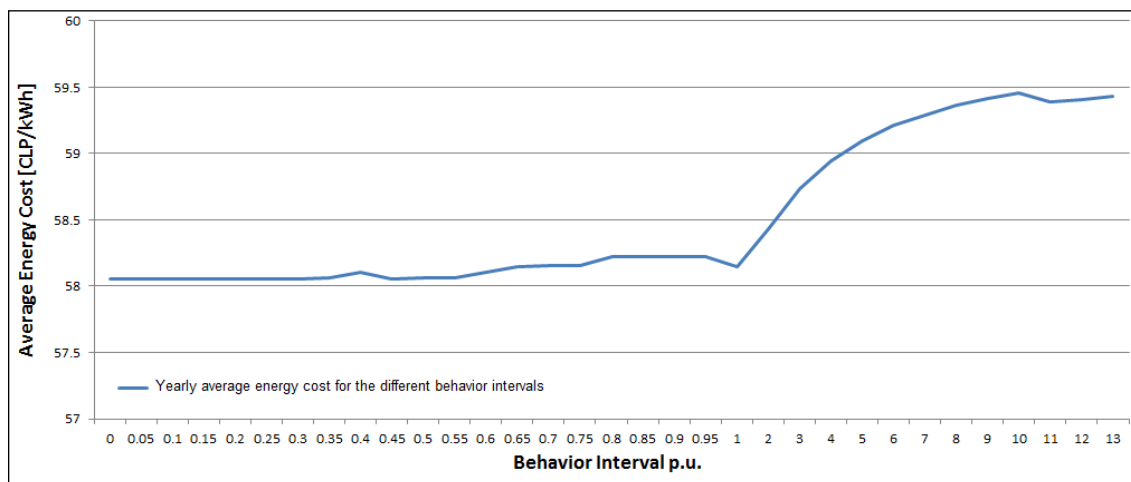
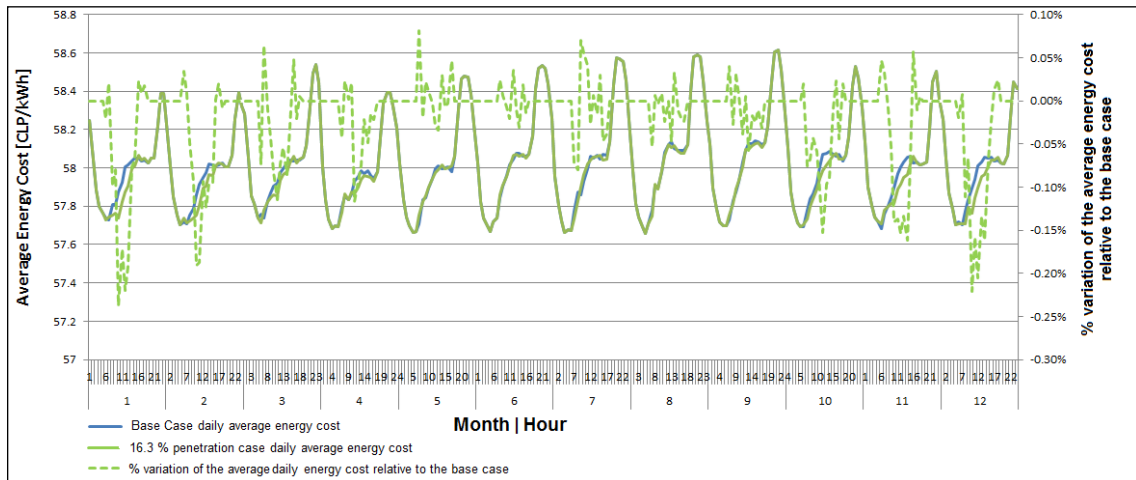


Figure 5-93: Yearly average energy with detail on low penetration scenarios

If the same exercise is repeated considering that no avoided energy losses payments are made to the DG owners by the surplus power injections to the network. Figure 5-94 shows the exercise with monthly and hourly resolution for the first year of operation for a 1 p.u. behavior interval. In this figure the hourly average energy cost decreases during solar hours, explaining that this bonus payment for losses, under the actual tariff scheme. When the yearly average energy cost is compared against the behavior interval (or penetration under same configuration of embedded generation) it can be seen that lower energy costs are achieved (Figure 5-95). Though there is a decrease at the energy purchase cost, this decrease is low (lower than 1 %). If the overall impact could be measured (transmission system losses, lower marginal technology per hour) the impact would be bigger and we would have a better understanding of the real impact of DG penetration.



6 DISCUSSION

The use of a balanced electric model could underestimate the technical impacts such as static voltage stability and power and energy losses because of the greater unbalances that the penetration of PV DG could create. The use of equal demand modulation curves with hourly resolution on every consumer could hide technical dynamics such as fast apparent consumption/generation variations which could trigger overvoltages and/or thermal capacity violations during short periods of time. The use of these curves could also change the full energized tariff (BT1) economic operational outcomes, because of the sensitivity that this tariff has with the change in the direction of the active power flows at the consumer metering point. Non-energized tariffs would have the same issue because of the value at which the distribution company has to buy the surplus energy to the DG owner, changing the average cost of energy that the DNO has to pay in order to meet the demand needs. The cost for knowing the voltage magnitudes for the tap changer case throughout the distribution feeders is neglected, thus the economic signals lack the cost of voltage measurement equipment that would increase the cost per kW or MWh under large penetrations of DG. Change in protection scheme costs are also neglected, this could also impact by increasing the cost per installed kW or consumed MWh, not only when capacity related investments are required but also at lower penetrations, increasing the penetration window at which DG causes investment costs.

7 CONCLUSIONS

This work proposes a methodology to analyze the technical and economic impact of the integration of the integration of DG on real size distribution feeders, allowing different tariff scheme's performance to be measured and to quantify the capacity related investments that DG triggers for a given network topology and penetration scenario.

The proposed methodology adds a parameterized relation between the amount of installable DG power and the size of the client, which gives an economic base to the process of random penetration scenarios. This methodology also adds an interface which decreases the volume of data that the operational model exports to the economic mode. This is possible using the net present energy and power value with a certain decomposition of the demand-generation curve present at each client connection point.

The model was used to test the impact of PV DG on real size distribution feeders under the Chilean regulation proving that solar PV DG penetration has a negative impact on the economic operation of distribution companies under the present given tariff schemes.

The current tariffs do not capture the benefit of loss reduction caused by low penetrations of DG. The lower energy consumption that goes in hand with DG penetration has a negative economic impact under the current regulation and given the stagnant trends of growth of regulated electric energy consumption, the current tariffs are a short term threat for the distribution industry, assuming that DG would be a reality.

The parameters that affect the profit of the distribution companies the most are the penetration percentage and the behavior interval (installed power to demand size ratio)

for a given penetration value. There was no significant difference of profit changes for difference size clients.

A proposed tariff, based on an existing modified energized tariff, showed that a positive economic impact can be obtained under the presence of DG. This tariff is ambitious in terms of monitoring clients, therefore hard to put in practice, but shows that solutions can be found that promote these new energy agent's that clean the energy matrix and increase the amount of generators, increasing the competition. This proposed tariff still carries the flaw of the energized fixed costs, which brings uncertainty to the network owner that is being regulated, by not knowing if the price cap, given by the state regulator, will be enough to cover the expected return for his investments.

It was demonstrated that under the actual scheme of paying to the DG owner the average avoided losses produces higher energy purchase costs that impact negatively to the distribution company. By eliminating this avoided losses component the average energy purchase cost decreases slightly, leaving the distribution company indifferent in terms of energy purchase cost, but still, the penetration of DG takes part of the size of the energy market, decreasing the quantity of energy that the distribution company sells. This last concept is a sign to change the volumetric tariff system that we have to charge certain costs to the end user.

Although this paper studies the economic impact of DG penetration, technical impacts can't be left aside. Unfeasible scenarios can't be allowed, because of the quality of product that the distribution companies have to meet at consumer level, therefore the new regulation has to take care that no electric quality is being loss as a consequence of DG. In this line, the limitation of installed power relative to the design load size of a

consumer showed to be an effective way for controlling overvoltages. This per unit power limitation also demonstrated to be an effective way of limiting the capacity related reinforcement's that have to be done to the network in order to avoid thermal capacity violations.

Capacity related investments are needed for medium and higher DG penetration scenarios. Two ways of recovering these costs were analyzed, direct cost of connection per installed kW and socialized cost per consumed kWh. These costs, in both cases, are additive for the average consumer tariff and the selection of the recovery system depends on the legislative goals that the country has.

8 STUDY CASE RECOMMENDATIONS

The actual Chilean regulation presents, throughout the day, a single energy loss expansion coefficient, lacking temporary and spatial signals that could help giving a more accurate economic value to the average avoided energy losses plus a better use of the distribution network. By calculating the average energy losses expansion coefficient for more than one time period a day, the market could solve a configuration of distributed energy sources that inject power during peak demand hours, decreasing the amount of losses and improving the efficiency of the network.

The same regulation keeps distribution business merged with the commercialization of electric energy. This business structure could inhibit the creation of business models such as the distributed generation aggregators, who buy the power generated by multiple rooftop solar panels on a given granted distribution zone, acting as a generator and a new agent at the energy market, narrowing the possibilities of increasing the competition on the electricity markets. Apart from that, the unbundling of the distribution and commercialization business could allow the distribution tariffs to evolve, into what experts say, an analogy of the telecommunication industry [20]. Electric clients could select the tariff in terms of power (bandwidth) and time (coverage) of usage, paying for “tailored” tariffs that could lower the cost that pay the clients for their current energy consumption.

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10 ANNEX

1 BT1 tariff components

BT1			
Charge	Unit	Formula	
Fixed	USD/client	$CFES$	
Transmission System Use Charge	USD/kWh	CU	
Base Energy	USD/kWh	$PEBT \times PEAT \times P_e + \frac{PPBT \times PPAT \times P_p}{NHUNB} + \frac{CDBT}{NHUDB}$	
Winter Additional Energy	USD/kWh	$PEBT \times PEAT \times P_e + \frac{2.4 \times PPBT \times PPAT \times P_p}{NHUNI} + \frac{2.4 \times CDBT}{NHUDI}$	

2 BT2 tariff components

BT2			
Charge	Unit	Formula	
Fixed	USD/client	$CFES$	
Transmission System Use Charge	USD/kWh	CU	
Energy	USD/kWh	$PEBT \times PEAT \times P_e$	
Power during peak demand	USD/kW/Month	$FNPPB \times PPBT \times PPAT \times P_p + FDPPB \times CDBT$	
Partial Power during peak demand	USD/kW/Month	$FNDPB \times PPBT \times PPAT \times P_p + FDDPB \times CDBT$	

3 Economical logic of rooftop solar PV installation

Given the actual regulation (or lack of it), captive consumers face the option of installing rooftop PV generation to decrease the consumed energy measurements, lowering the tariff cost by means of local power generation. During a normal day this generated power can be greater than the existing load in the given service point, giving as a result a power injection to the network. This injected power is priced at the energy cost plus the avoided average losses value, which is lower than the complete tariff that a non DG user pays for consuming a kWh. This creates the economic logic that a private rooftop generator will maximize the value of its generated energy by minimizing the injected energy back to the network. This phenomenon can be seen by doing an economic evaluation of installing rooftop PV on consumers under the Chilean regulation assuming monthly consumption-generation metering.

The used model took in consideration actual solar panel kit prices existing in the market for any normal person to buy. The same solar radiation database was used for this economic analysis [8]. A yearly 10 % discount rate was used for the cash flows. Actual regulated tariff prices were used. The consumption profiles are shown in figure 12:

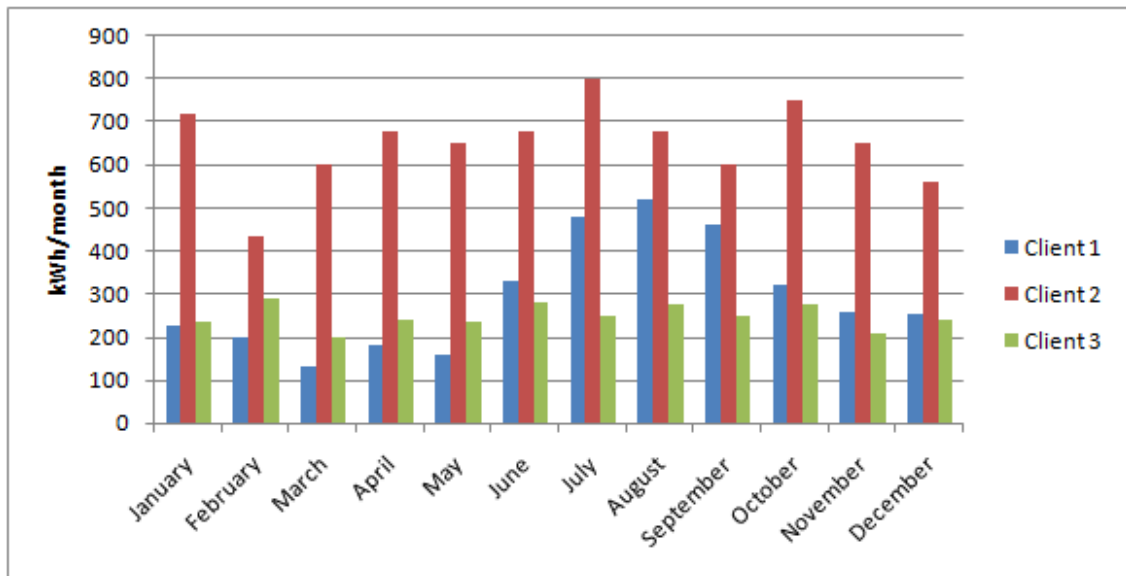


Figure 12: Monthly consumption of real Chilean regulated clients

Each client was analyzed in order to obtain the optimal amount of installed rooftop solar power that would maximize the annual rate of return for a 25 year evaluation horizon and minimize the payback time.

	Client 1	Client 2	Client 3
Installed			
kW	1.84	1.84	2.99
Annual			
Rate of	1.15%	1.23%	1.72%
Return			

Table 2: Economic analysis results

This results suggest that the bigger the client the less energy that is going to be injected back to the network, hence maximizing the price of the sold energy. Giving as a result that the bigger the client the more incentive it has to stop consuming from the network.

4 Conductor Cost

12 kV Aerial Conductors			
Conductor	Section [mm2]	R [Ohm/km]	Cost [MUS\$/km]
AAL025AAAC	25	1.248	3.3
AAL035AAAC	35	0.891	3.6
AAL070AAAC	70	0.495	4.5
AAL120AAAC	120	0.345	5.9
AAL300AAAC	300	0.116	15.5
ASC300_12x2	300	0.058	35.0

12 kV Underground Conductors			
Conductor	Section [mm2]	R [Ohm/km]	Cost [MUS\$/km]
SAL050_12	50	0.721	28.0
SAL070_12	70	0.495	29.0
SAL120_12	120	0.345	31.3
SAL240_12	240	0.144	39.2
SAL400_12	400	0.087	52.0
SAL630_12	630	0.055	69.1

23 kV Aerial Conductors			
Conductor	Section [mm2]	R [Ohm/km]	Cost [MUS\$/km]
AAL025AAAC_23	25	1.248	3.3
AAL035AAAC_23	35	0.891	3.6
AAL070AAAC_23	70	0.495	4.5
AAL120AAAC_23	120	0.345	5.9
AAL300AAAC_23	300	0.116	15.5
ASC300_12x2	300	0.058	40.2

23 k Underground Conductors			
Conductor	Section [mm2]	R [Ohm/km]	Cost [MUS\$/km]
SAL050_23	50	0.721	25.3
SAL070_23	70	0.495	29.0
SAL120_23	120	0.345	34.2
SAL240_23	240	0.144	46.5
SAL400_23	400	0.087	69.7
SAL630_23	630	0.055	87.3

0.4 kV Aerial Conductors			
Conductor	Section [mm ²]	R [Ohm/km]	Cost [MUS\$/km]
AAL025AAAC_BT	25	1.248	2.4
AAL035AAAC_BT	35	0.891	2.7
AAL050AAAC_BT	50	0.721	2.8
AAL070AAAC_BT	70	0.495	4.2
APR3F95	95	0.331	6.3
AAL240AAAC_BT	240	0.144	10.9
AAL300AAAC_BT	300	0.116	11.8

5 Variation of the networks reactive consumption

Low solar PV DG penetrations decrease the consumption of active power throughout the network. For high penetration scenarios, the active power flows can even suffer inversions, flowing from the consumer in direction to the feeder's header.

This decrease in active power consumption, apart from decreasing voltage drops through a branch, causes a separation of angles of the voltage phasors of the buses at the extremes of the given branch. This angle opening causes an increase of reactive consumption of the network, increasing the reactive power flow demand at the feeder's header and throughout the network.

Figure 96 presents the voltage phasor's angular difference and the active power flows for an embedded active power injection which doesn't produce inversion of active power flows. This injection of 25 % of behavior interval (25 % relative to the

design load size) causes an increase of angular difference, changing from -0.00008 to -0.00016 radians at noon. When the injected active power increases, the angle difference also increases. Figure 96 also presents the case when active power flows suffer an inversion, where the angular difference keeps getting larger (50 % of behavior interval).

High penetration scenarios (4 p.u. behavior interval) cause a bigger angular difference with an increase of reactive power of the network. This accumulative increase in reactive consumption could impact the upper sections of the network when facing high demand of thermal capacities during the day.

Figure 96: Active power flow and voltage phasor angular difference under active power injection at a distribution network

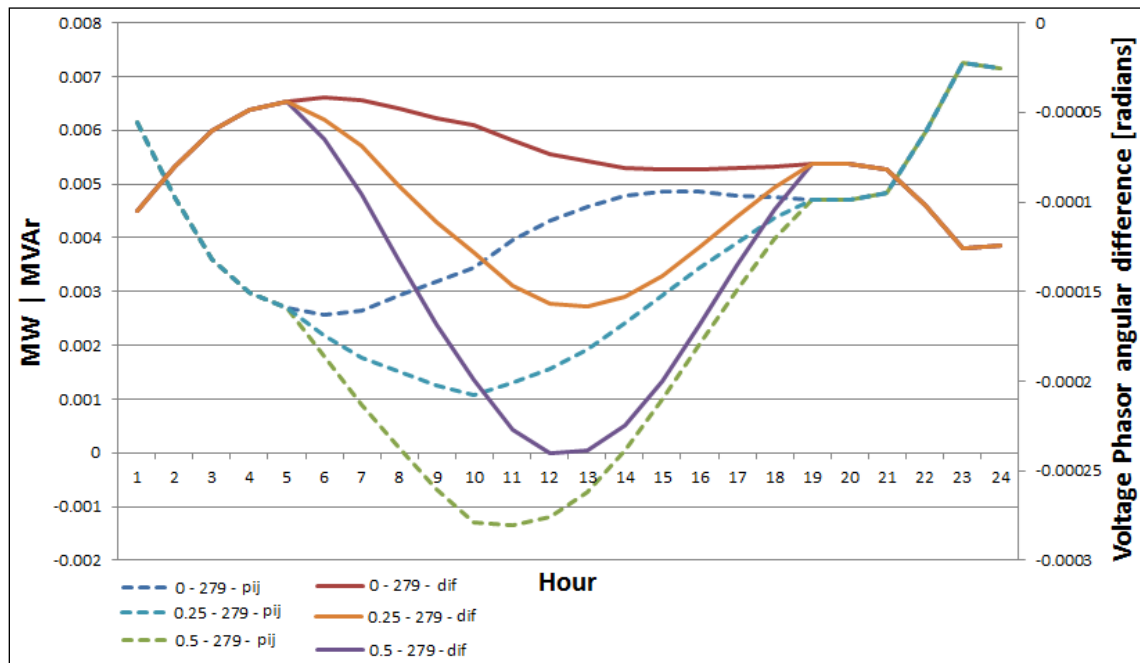
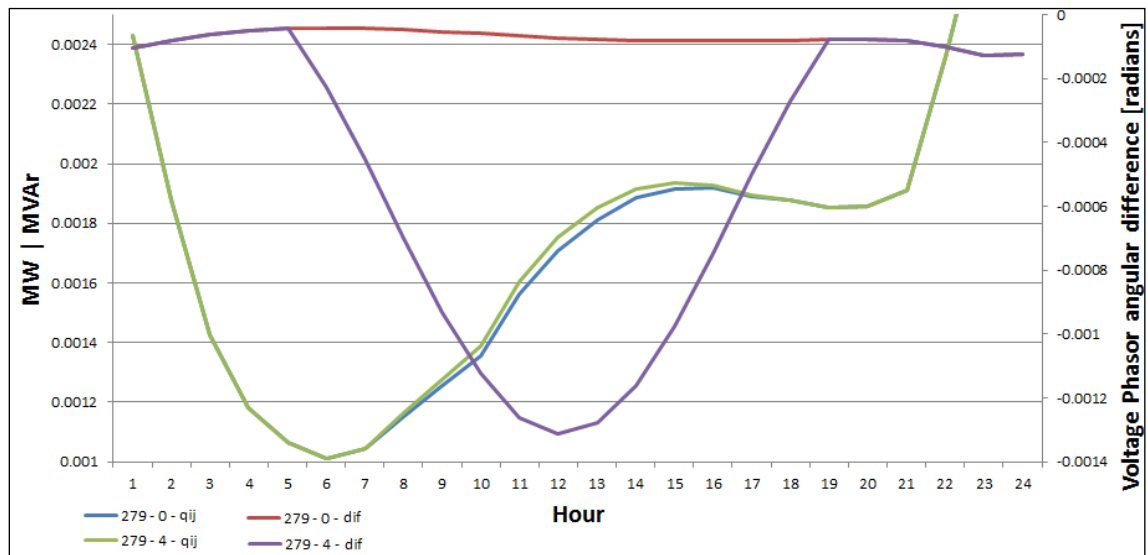


Figure 97: Reactive power flow and voltage phasor angular difference under high active power injections at a distribution network



6 Spanish Tariffs definition of periods

