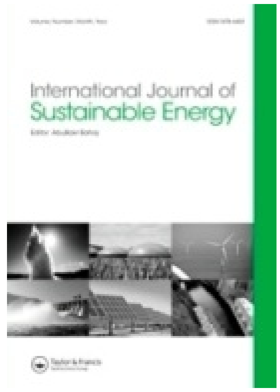

An optimal solution for reactive power re-dispatch agency using open-source restructuring learning semantic networks

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An optimal solution for reactive power re-dispatch agency using open-source restructuring learning semantic networks.

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An optimal solution for reactive power re-dispatch agency using open-source restructuring learning semantic networks.

This research proposes a model for performing a re-dispatch of reactive power in the Ecuadorian electricity system using reactive power produced by generators and compensators found throughout the network. Electricity plays a very important role in the development of a country, currently in Ecuador most of the power stations are in the east of the country whereas the biggest city is on the west and for that reason there is a complex network that allow power transmission from generation to the point of consumption. The efficient use of energy is considered in the energy losses that are reduced by applying reactive power optimization, which also has other benefits such as maintaining the voltage profile in the entire grid according to regulations. This paper is focused on an optimal solution for reactive power re-dispatch agency using open-source restructuring learning semantic networks. For this, an Optimal Power Flow (OPF) is modelled, where the objective function will be to reduce the losses in our transmission system, considering operating limits and balances of active and reactive power in each of the nodes of the system. As a result of the optimal flow model, the reactive power that each agent provides, achieve a safe, reliable, and optimal system. This research uses GAMS over two case studies Milagro-Molino and Santa Rosa-Totoras. The results of restructuring semantic networks indicate higher interactivity in agent creation, patterns, suggesting a fast learning, motivation, and sustainability of solutions. The solver results show that the solution is a Local Optimal.

Keywords: semantic model; learning analytics; energy agency; non-linear optimization; optimal reactive power dispatch; linear programming approach; voltage stability assessment; voltage profile improvement.

Introduction

The dynamic dispatch problem differs from the static economic dispatch problem in that it includes a generator ramp rate constraint. There are two different formulations of this problem. (i) dynamic optimal control dispatch (with a ramp rate as an input variable), where optimization is performed at optimal control setting; and (ii) a dynamic economic dispatch where optimization is done with respect to the dispatchable power of the committed generation units (Xia, 2010). This paper follows the later approach. Dispatch literature such as Chen (2005) and Rayudu (2016) deal with optimizing of power dispatch systems, aiming at minimising the cost to deliver power for real and complex dispatch systems. Researchers have identified many important practical issues to consider when modelling the dispatch system; including generators power limits outputs, spinning reserve requirements, group power import/export limits, transmission losses, multiple fuels, and others (Hindi, 1991). Surender et al. (2011) developed on IEEE 30 bus system a multi-objective reactive power price clearing (RPPC) mechanism using voltage dependent load model and voltage stability. They showed that the loss minimization (LM) and the Total Payment Function (TPF) minimization do not make valid single or joint objectives due to reduction of load served. Surender et al. (2016) developed also on IEEE 30 bus a multi-objective centralized optimal day-ahead coupled energy and reactive power scheduling with voltage dependent load modelling. The Pareto curve allows the decision maker to make a better informed decision, regarding the compromise between the conflicting objectives. Surender (2017) presented a meta-heuristic based Cuckoo Search Algorithm (CSA) for solving the optimal reactive power scheduling problem considering the generator voltages, transformer tap settings and switchable shunt VAR sources as the control variables for achieving the optimum transmission losses.

A Semantic network is a way of representing the relationships between objects and ideas. In our research there are regulations that set limits on how much the voltage magnitude varies to maintain quality and safety guidelines, the utility supply voltage must be reasonably free from harmonics, and any voltage fluctuations must be within tolerance. Santos (2013) proposes an ontology for integrating the basic concepts needed to interpret all the information available from a power system. Our research proposes an optimal solution using an open-source approach.

The National Transmission Grid (NTG) supply voltage deviates from the ideal due to events such as faults; switching lines, loads, or system equipment; overloads and light loads; and loads that inject harmonics into the utility system. For Ecuador the National Electricity Regulatory authority (ARCONEL) established these guidelines shown in Table 1, where values are in percentage for lower (l) and upper (u) voltages (Transelectric, 2020).

Table 1. Band voltage variation for different voltage levels

Voltage	l normal	l emergency	u normal	u emergency
500 kV	-5%	-8%	5%	7%
230 kV	-5%	-7%	5%	6%
138 kV	-5%	-10%	5%	6%
69 kV	-3%	-5%	4%	6%

The short-term reactive power dispatch problem works to minimize active power transmission losses, and the voltage profile is also improved with constraints. The operational constraints (state and control variables) contain reactive power sources, bus voltages, phase angle and transformer tap setting (Zhao, 2005). As shown in Figure 1, historically the annual energy loss rate is about 3% in the NTG. Transmission loss is formulated as a cosine functions and non-linear programming technique is used to solve these problems. For computational efficiency, we approximate the cosine function as a quadratic function and solve the problem using a static piecewise linearisation method. This research proposes a dynamic piecewise linearisation model (Rewienski, 2006), that leads to increased computational efficiency.

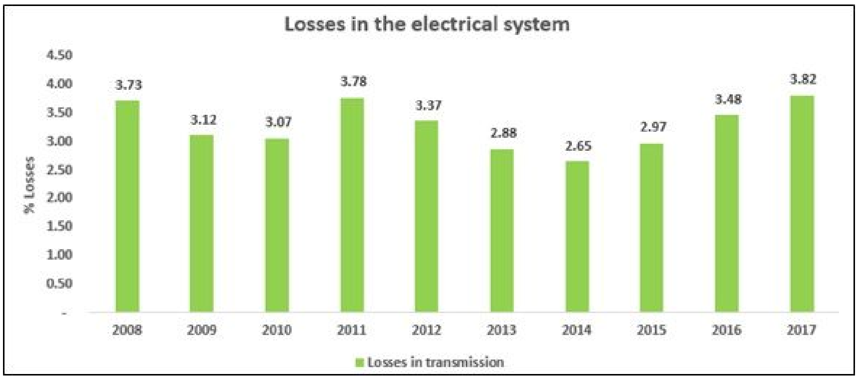

Figure1. Transmission losses statistics

In order to be able to diagnose the operating conditions of the NTG, the Ecuadorian power supply installations were divided into operation zones, therefore, the grid topology group is shown in the Figure 2 (MEER, 2017). In order to keep the system voltage in the optimal range and prevent the voltage instability phenomenon before it occurs, this research divides the control voltage and the reactive power into two sub-problems and proposes the line agents to cooperate in the NTG 'voltage control' and 'reactive power control'. The transmission line agent predicts voltage fluctuations after power flow to adjust reactive power and determines whether restructuring of the power grid is necessary. The proposed structure allows semantically connections between transmission lines, generator units and loads.

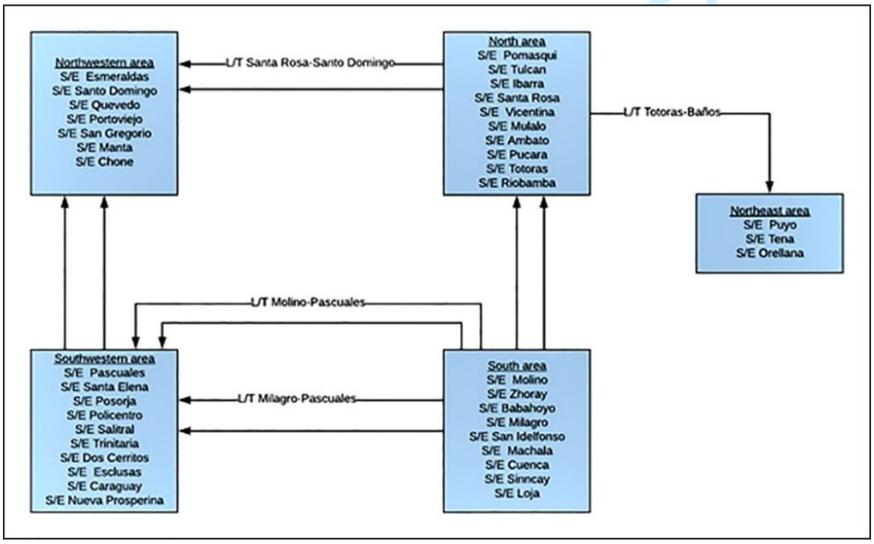

Figure 2. Operational zones of the NTG

A Semantic Network (SN) is a graph structure for representing knowledge in the form of patterns of interconnected nodes and arcs. A semantic network not only store knowledge but also the associative related connections which makes items of information being accessible to others. What is common to all semantic networks is a "*declarative graphic representation that can be used to represent knowledge and support an automated systems for reasoning about that knowledge in an abstraction suitable for processing by a computer program*" (McIntosh 2000, Lehmann 1992). Sowa (2014) argues that the most common kinds of semantic networks are (i) *Definitional networks* that involve definitional connections between concepts, (ii) *assertional networks* are designed to assert propositions. The term propositional SN is used to distinguish those networks in which every assertion is considered as a concept and represented by a node, from those in which assertions are represented by arcs and subset relationships or statements (Maida, 1982), (iii) *implicational networks* use implication as the "*primary relation for connecting nodes to represent patterns of belief, causality, or reasoning*", (iv) *executable networks* "*which can perform inferences, pass messages, or search for patterns and associations*", (v) a *learning network* builds or extends by acquiring knowledge from examples, and (vi) *hybrid networks* combine two or more of the previous techniques, either in a single network or in separate but closely interacting networks.

A Systems using a network representation can modify the network in three ways: (i) Rote memory. The simplest form of learning is to transform new information into the network and add into the current network without further modification (Cohen, 2016), (ii) Changing the weights. Some networks have numerical values, called weights, associated with the nodes and arcs (Khan, 2005). (iii) restructuring; The most complex form of learning makes fundamental changes to the structure of the network itself

(Batzias, 2002). This research uses restructuring learning systems.

This research argues that the reactive power re-dispatch is a learning semantic network, i.e., our goal is to include voltage constrains and permit selected buses to be a candidate for reactive power installation. The system must be restructured in a way that creates some constrains. The restating of this reactive power dispatch agency we refer as a restructuring the learning semantic network. Furthermore, this paper also shows the practical effect of using reactive power dispatch to reduce active power losses and improve the voltage profile of the transmission system.

Key components in restructuring the National Transmission semantic network.

An electrical power system is defined as a series of systems aimed at generating, transforming, transmitting, and distributing electrical energy to end-use consumers in an economical, safe, reliable, environmentally friendly, and socially responsible manner. Power systems provide essential services to society (Blackburn, 2014). Reactive power control plays a key role in maintaining a secure voltage profile in a large-scale transmission system. This is essential for the operation of electromagnetic energy devices producing magnetic fields. In some cases, it is injected into the power system network to maintain a higher node voltage.

Generation

The concept of power generation is based on converting mechanical, hydraulic, thermal, wind, or other types of energy into electricity. Ecuador's available electricity generation consists of sixteen state owned hydroelectric plants and thirty-nine small hydroelectric plants owned by electric distribution companies, municipalities, and private companies, and over a hundred thermal power plants. As shown in Table 2 (ARCONEL, 2022), renewable plants are 60.77% and non-renewable: Internal Combustion Engine (ICE), Turbo-gas and Turbo-vapour are 39.23% of the total generation.

Table 2. Electricity generation in Ecuador

Generation fuel	Capacity (MW)	Percentage
Hydraulic	5,106.85	58.45
Wind	21.15	0.24
Non-renewable	3,427.33	39.23
Biomass	144.30	1.65
Photovoltaic	28.65	0.33
Biogas	8.32	0.10
Total	**8,736.60**	**100**

Compensation

Capacitive shunt reactive compensation is one of the most commonly used due to its advantages in system response. Benefits include optimization of reactive power flow optimization, voltage regulation, system loss reduction, and power factor regulation. Traditionally, planners used optimization techniques to determine the quantity and location of compensation systems. Power system compensation is performed by capacitor banks or inductances. These devices maintain the voltage profile of the NTG bus according to various demand conditions and regulations under both normal operating and emergency conditions (MEER, 2017). As shown in the Tables 3 and 4, the NTG has a total of 306 MVAR capacitive compensation devices and a total of 100 MVAR inductive compensation devices distributed in various substations across the country (MEER, 2017).

Economic dispatch of the generation units

Power systems are intended for economic performance on investment. Managing the economics of power grids is highly complex and involves a variety of financial, tariffs, social, business, environmental, legal, and operational issues. In

Ecuador, such regulation is carried out by Arconel, and economic dispatch is carried out by the national electricity operator (Cenace) (ARCONEL, 2000). Cenace uses an optimization model that achieves the lowest production costs while always guaranteeing the quality and safety of existing conditions, with short-term economical dispatch depending on operating system limitations (Blackburn, 2014).

Table 3. Location of the NTG capacitive compensators

Substation	Voltage level (kV)	Banks (Number)	Capacity (MVAR)	Total (MVAR)
Santa Rosa	138	3	27	81
Pascuales	138	2	30	60
Santa Elena	69	1	12	12
Loja	69	1	12	12
Portoviejo	69	3	12	36
Pascuales	69	2	12	24
Esmeraldas	69	2	12	24
Policentro	13.8	2	6	12
Machala	13.8	2	6	12
Milagro	13.8	1	18	18
Tulcán	13.8	1	3	3
Ibarra	13.8	2	6	12
Total		**22**	**156**	**306**

Table 4. Location of NTG Inductive Compensators

Substation	Voltage level (kV)	Banks (Number)	Capacity (MVAR)	Total (MVAR)
Pascuales	13.8	2	10	20
Molino	13.8	2	10	20
Santa Rosa	13.8	2	10	20
Quevedo	13.8	1	10	10
Santo Domingo	13.8	1	10	10
Totoras	13.8	1	10	10
Riobamba	13.8	1	18	10
Total		**10**	**70**	**100**

To execute the dispatch, they use a hydro-thermal coordination software. Figure 3 shows a block diagram of the dispatch methodology (ARCONEL, 2000).

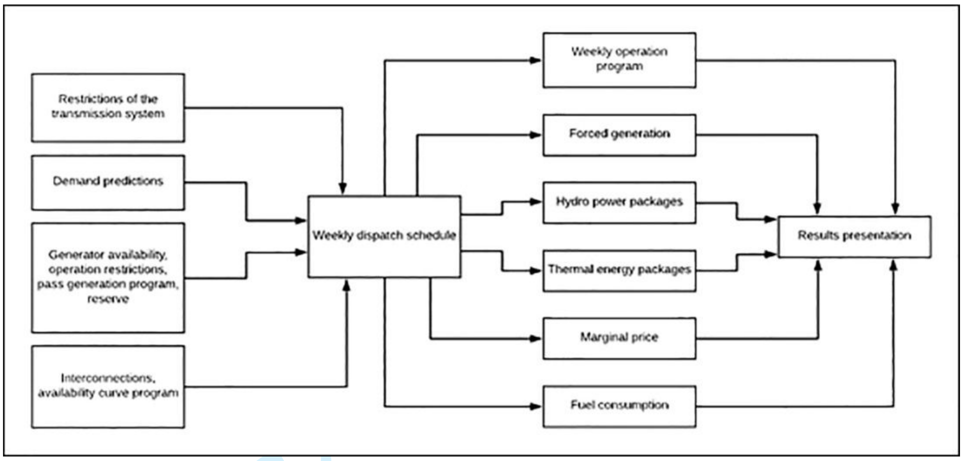

Figure3. Cenace economic dispatch methodology

The economic dispatch problem is determining the level of generation that minimizes the total cost of generation for a defined load level. See Seifi and Sepasian (2011)

Objective Function: Minimize the production cost of the entire electric power system.

Constrains

1) Total power generation should be equal to total load.

2) Transmission network constrains resulting from the following considerations: Kirchhoff's law, transmission line constrains, topologies, line losses, transformers and safety constrains.

3) Daily energy allocations based on the annual operative plan.

4) Generators layout with values of P_{min}, P_{max}, spinning reserve margin.

5) Availability of steam units.

If no optimal solution for economic dispatch is found, Cenace relaxes the optimization model constrains and does this in a priority scheme until it reaches the optimal solution. It is important to remember that the appropriate authorities must be notified if such action is taken (CONELEC, 2000).

In summary, this research proposes an optimal solution by a re-dispatch agency of reactive power using restructuring learning approach. The optimization strategy is to regulate the voltage profiles in each node, as well as reducing losses. The model is non-linear, and the solution is open source using the General Algebraic Modelling System (GAMS). GAMS allows modelers to translate real world optimization problems into computer code.

Methodology

The modelling process is broken down into three separate phases: first section describes the data and network parameters; section two describes the state and control variables, and section third explains the reactive power dispatch optimization model (objective function and restrictions). Figure 4 shows a schematic flowchart overview of the methodology and modelling methods.

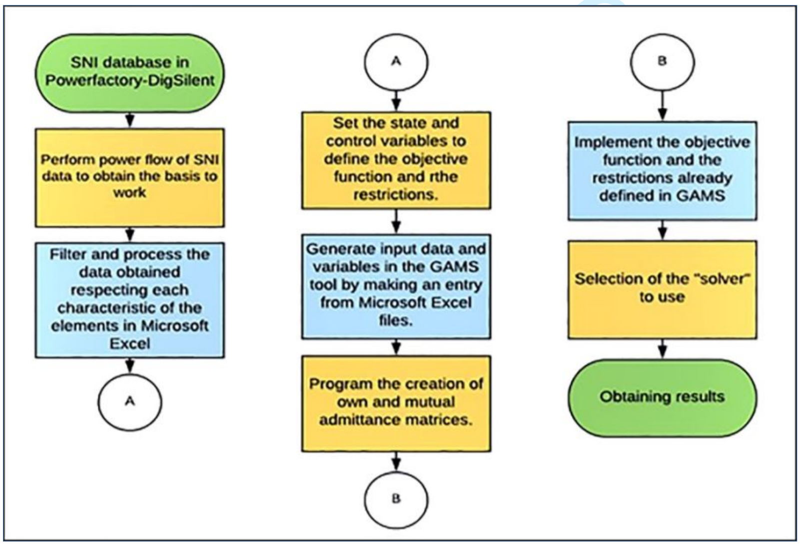

Figure 4. Methodology and modelling methods

Figure 4 also shows how to solve the mathematical model using computational tools such as Excel Solver and GAMS. These tools solve the optimization models modelled by non-linear methods. From the simplest to the most complex systems, it shows how the variables, limitations and restrictions affect results. An important part of our research is demonstrating the use of a general purpose open-source code (in our case, BONMIN) to solve a nonlinear optimization problem. Excel was used as the common evaluator of our GAMS design; therefore, the quality of the solutions can be compared independently of BONMIN.

Data and network parameters for input the power flow.

The transmission line admittance Y_{ij} is composed by the own and mutual admittance that make up the admittance matrix of the bus, see Equation 1. For a full mathematical formulation of the power flow equations, see Seifi and Sepasian (2011).

$$Y_{ij} = |Y_{ij}|\angle\theta_{ij}\,;\ Y_{ij} = |Y_{ij}|\cos\theta_{ij} + j|Y_{ij}|\sin\theta_{ij} = G_{ij} + jB_{ij} \qquad (1)$$

Where $G_{ij} = \frac{R_{ij}}{R_{ij}^2 + X_{ij}^2}$ and $B_{ij} = \frac{X_{ij}}{R_{ij}^2 + X_{ij}^2}$

The total real power P_i and reactive power Q_i entering the system through the bus is given in Equation 2. The active power is in Equation 3 and the reactive power is in Equation 4. Where V_i *is* the voltage magnitude, δ_i is the the voltage angle and the diagonal element Y_{ii} (self admittance of bus i) contains the sum of admittances of all the branches connected to bus (i). The off-diagonal element Y_{ij} (mutual admittance) is equal to the negative sum of the admittances between buses (i) and (j). B_{ij} is the reciprocal of the reactance between bus (i) and bus (j) i.e., B_{ij} is the imaginary part of Y_{ij} and G_{ij} the conductance.

$$P_i - jQ_i = Y_{ii}V_i^2 + V_i * \sum_{n=1}^{N} Y_{in}V_n,\ i \in N \quad (2)$$

$$P_i = |V_i^2|G_{ii} + \sum_{n=1}^{N} |V_iV_n|[G_{in}\cos(\delta_n - \delta_i) + B_{in}\sin(\delta_n - \delta_i)],\ i \in N \quad (3)$$

$$Q_i = -|V_i^2|B_{ii} + \sum_{n=1}^{N} |V_iV_n|[G_{in}\sin(\delta_n - \delta_i) - B_{in}\cos(\delta_n - \delta_i)],\ i \in N \quad (4)$$

State and control variables

The state and control variables in any node at the time of analysis are shown in Figure 5. P_g and Q_g are control variables, these are the generator active and reactive power, respectively. On the other hand, V and δ are the state variables corresponding to the voltage magnitude and angle, respectively.

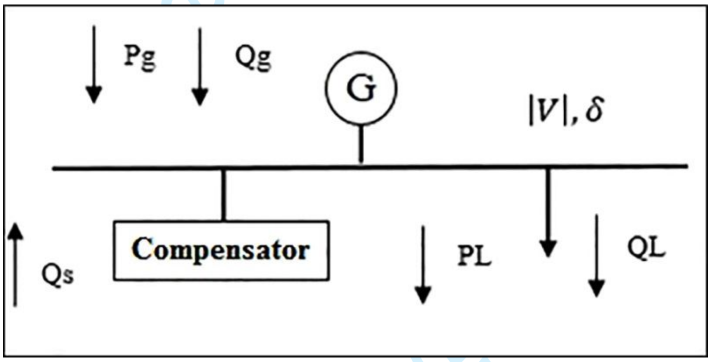

Figure 5. Node representation of an electrical system

Q_s is another control variable, responsible for injecting reactive power through capacitors or reactors compensators banks. Finally, P_L and Q_L, represent the load on each node or bus (Grainger, 1994).

The early stages of this research involved substantial data management, cleaning, restructuring and additions to the NTG initial data set in DIgSILENT PowerFactory (PF). The active power generation economic dispatch is carried out by Cenace; therefore, this study was only conducted in the reactive power agency, i.e., the dispatch of active power of the generators was omitted in the entire generation dispatch process, therefore, this research deals with the reactive power re-dispatch agency.

Optimal reactive power dispatch model formulation

OPF consists of dispatching generators to minimize or maximize an objective function (see Equation 5), which is intended to minimize losses in the transmission lines of the system, subject to equality and inequality restrictions. This research focus on the re-dispatch of reactive power, to achieve this a restructuring learning of the NTG semantic network is proposed. It was necessary to solve the non-linear active and reactive power flow equations.

$$\min f(x); \quad subject\ to \quad g(x) = 0; \quad h(x) \leq C \tag{5}$$

The main objective is to find the reactive power supplied by the NTG generators and compensators to reduce the level of power losses in the transmission line, also reduce the operating cost and respect the operation and restriction rates of each variable. The objective function therefore corresponds to the total active power losses in the transmission lines as seen in Equation 6. Where K is the line number.

$$Losses_{line\ K} = \sum_{K \in NL} G_{in}\left(V_i^2 + V_n^2 - 2V_iV_n\cos\delta_{in}\right) \tag{6}$$

For simple systems, Equation 6 of the sum of the active power losses of all the transmission lines was used directly, but for complex systems another objective function, where the reactive power losses are minimized and yields the same results, is used, see Equation 7.

$$Q_L = \sum_{i=1}^{n} Q_{gi} + \sum_{i=1}^{n} Q_{ci} - \sum_{i=1}^{n} Q_{di} \tag{7}$$

Where Q_L is the system reactive power loss, Q_{gi} is the reactive power generated in the bus (i), Q_{ci} reactive power injected or condenser (i), and Q_{di} is the reactive power demanded in the bus (i).

Active power balance restrictions

The power generated in each of the buses should be equal to the power consumed, in order to maintain an active power balance, i.e., the generated active power P_{gi} must be equal to the sum of the demanding power of the load P_{di} plus the injected power P_i to each bus (Grainger, 1994). As seen in Equations 8 and 9.

$$P_i = |V_i^2|G_{ii} + \sum_{n=1}^{N} |V_i V_n| [G_{in} \cos(\delta_n - \delta_i) + B_{in} \sin(\delta_n - \delta_i)],\ i \in N \quad (8)$$

$$P_{gi} - P_{fi} - P_{di} + P_{ajust} - P_i = 0 \quad (9)$$

Where P_{gi} is the active power generated in the bus (i); $P_{di}$is the active power demanded in the bus (i); P_i is the active power injected in the bus (i); P_{ajust} is the active adjustment power; V_i, V_n is the voltage in the bus i and bus n, respectively; δ_i,δ_n is the angle of tension in bus i and bus n, respectively; G_{in} is the conductance between buses and n; B_{in} is the susceptance between buses i and n; N is the number of buses.

P_{fi} is the failure power, i.e., not served in the load, P_{ajust} represents an adjustment value to the active power generated. Because the losses were not known until final dispatch is available, an adjustment power was assigned to the slack bar or the bar where the cheapest generator is located and thus represent the losses of the system. Failure power was not considered in this research (GomezExposito, 2018).

As well as changes had to be made in the objective function, the adjustment power in the active power balance for more complex systems was eliminated because the quantities of losses that are reduced are of greater magnitude. It is necessary to establish the power generation as a variable and thus reduce the generation in the optimal points, taking as initial data the previous dispatch for a fast convergence at the time of programming. Another very important consideration that should have considered is that the active power previously generated and calculated with the economic dispatch might not vary too much, so an operating range of plus and minus five percent was established.

Reactive power balance restrictions

In the reactive power balance, the generated reactive power Q_{gi} must be equal to the sum of the reactive power demanded Q_{di} plus the injected power $Q_i$through the lines to each one of the buses and the reactive power Q_{si} that contribute each of the network compensators (Grainger, 1994). As seen in Equations 10 and 11.

$$Q_i = -\left|V_i^2\right| B_{ii} + \sum_{n=1}^{N} \left|V_i V_n\right| \left[G_{in} \sin\left(\delta_n - \delta_i\right) - B_{in} \cos\left(\delta_n - \delta_i\right)\right],\ i \in N \qquad (10)$$

$$Q_{gi} - Q_{fi} - Q_{si} - Q_{di} - Q_i = 0 \qquad (11)$$

Where Q_{gi} is the reactive power generated in the bus *i*;Q_{di} is the reactive power demanded in the bus *i*; Q_i is the reactive power injected in the bus *i*; Q_{si} is the reactive power in the reactors in the bus *i*; V_i, V_n is the voltage in bus *i* and bus *n*, respectively; δ_i, δ_n is the angle of tension in bus *i* and bus n, respectively; G_{in} is the conductance between buses *i* and *n*; B_{in} is the susceptance between buses *i* and *n*; *N* is the number of buses

Reactive power generators restrictions

This restriction depends on the characteristics of each of the generators of the system, depending on the operating active power, their capacity curve provides the maximum and minimum limits of reactive power it can provide.

$$Q_{gimin} \leq Q_{gi}\ ; Q_{gi} \leq Q_{gimax} \qquad (12)$$

Where Q_{gimin} is the minimum reactive power for the generator; in the bus *i*; Q_{gimax} is the maximum reactive power for the generator in the bus *i*.

Nodal voltages restrictions

This restriction applies in the voltage range and considers the minimum and maximum voltage level ranges in the NTG according to Arconel. As seen in Equation 13.

$$V_{imin} \leq V_i;\ V_i \leq V_{imax} \tag{13}$$

Where V_{imin} is the minimum voltage value in the bus i; V_{imax} is the maximum voltage value in the bus i.

Gamer solver

GAMS has a varied number of solvers for mathematical programming models. The **B**asic **O**pen-source **N**onlinear **M**ixed **IN**teger programming (Bonmin) is an open-source code for solving general Mixed Integer Nonlinear Programming (MINLP) problems which implements approximation algorithms and bypass branch, branch and cut, and external code (Bonami, 2013). Mathematically, the MINLP problem is represented in Equation 14.

$$maximize\ o\ minimize\ \ f(x) + Dy; \quad suject\ to\ \ g(x) + Hy\ \alpha\ 0\ ; \quad L \leq x \leq U;$$

$$y = \{0, 1, 2, \ldots\} \tag{14}$$

Where x is a vector of variables that are continuous real numbers, y is a vector that can only take integer variables, $f(x) + Dy$ is the objective function, $g(x) + Hy\ \alpha\ 0$ represents the set of constraints and L and U are lower and upper limit vectors in the variables.

The use of Excel is widespread in the power industry. It is a very powerful data analysis tool in a peripheral level. Excel is used in this research to detail each node in the system and the load connected to that node as well as lines characteristics, generators, and reactive power devices for the study. Spreadsheet data are then organized in a suitable format for import into a GAMS model. To export spreadsheet data to GAMS parameters, GAMS requires a strict format to be used inside the spreadsheet and needs a complex specification step where the data representation in the spreadsheet is described so that it can be understood by GAMS.

Results

This section shows the results after performing the simulations both in PF and GAMS. The research involves an extensive simplification and reduction modelling exercise of generators, lines and loads to focus in the area around the case study area as shown in the Figure 6. In this study it has followed the CELEC's criteria for selecting two zones, the first in green that corresponds to Molino-Milagro zone and the second in blue that corresponds to the Santa Rosa-Totora zone. This section shows the results from different transmission voltage levels, the reactive power re-dispatch from both the generators and the compensators and finally the losses reduction in both areas.

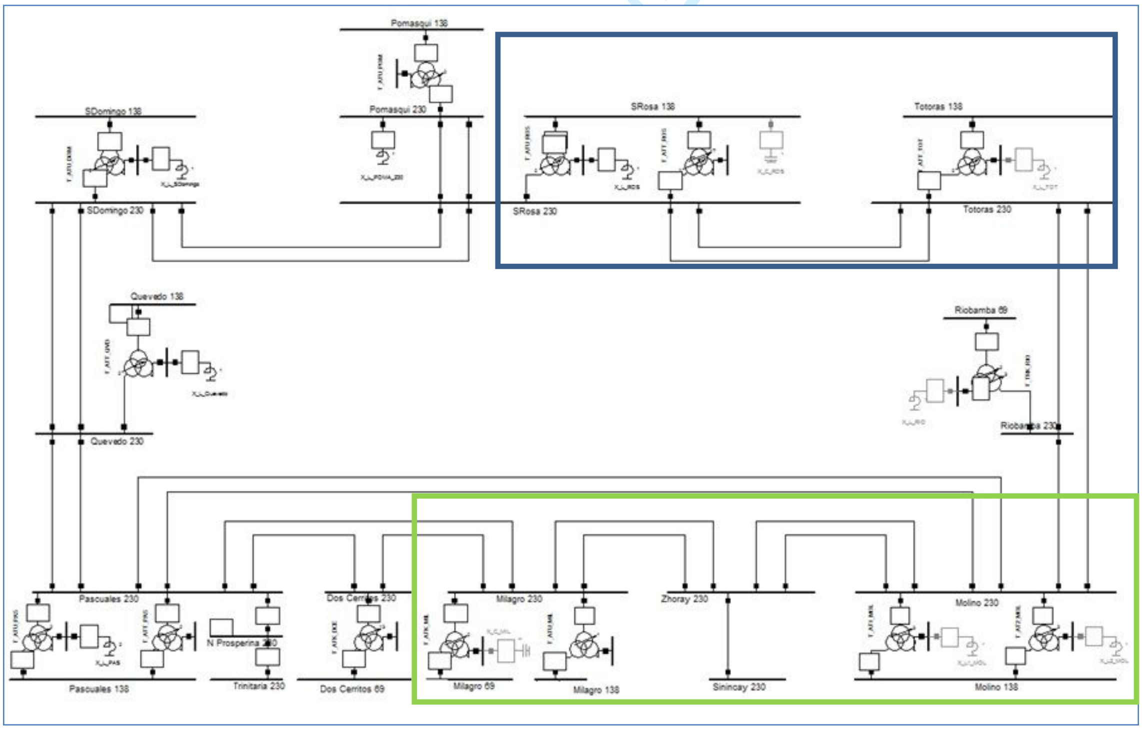

Figure 6. Santa Rosa – Totoras (blue) and Molino – Milagro (green) zones

The 230 kV transmission ring is made up of the circuits Molino - Milagro - Pascuales - Quevedo - Santo Domingo - Santa Rosa - Totoras - Riobamba – Molino. Molino Milagro zone corresponds to the southern part of the Ecuador and Santa Rosa Totoras zone corresponds to the northern part of the country. These areas were chosen because they are critical points of the system. In the event of the disturbances of these substations, the northern and southern areas of the country are left without service. The formulation of the Ecuadorian transmission expansion plan is carried out after the analysis of different technically achievable and economically viable equipment alternatives for high, medium and low demand conditions. Therefore, within each of the selected zones, different operating conditions of the NTG system were established: first high demand, then medium demand, and finally low demand.

High Demand Molino-Milagro zone

69 kV rating

From Figure 7, there is a change in the voltage levels after optimizing in most of the buses: Abanico, Alazan, Arenal, Corpache, Los Cerezos, Nuevo Parque industrial, SE11 Cuenca and Verdillo. The voltage level increases as seen in the Figure 7, but all are within the regulation levels.

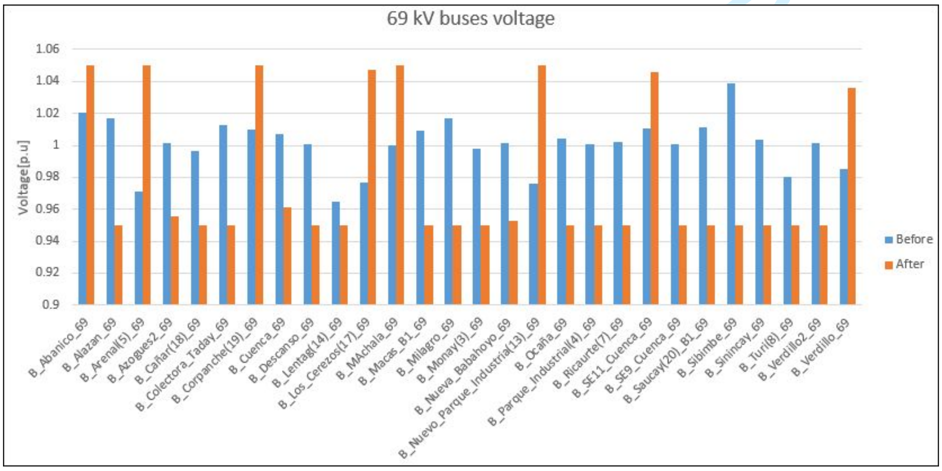

Figure 7. Peak demand Molino-Milagro 69 kV buses voltage before and after re-dispatch

138 kV rating

For most of the 138 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, the buses most affected are Cuenca, Gualaceo, Limon, Macas, Machala, Mendez, Nueva Babahoyo and San Idelfonso, but nevertheless, all are within regulation levels as seen in Figure 8.

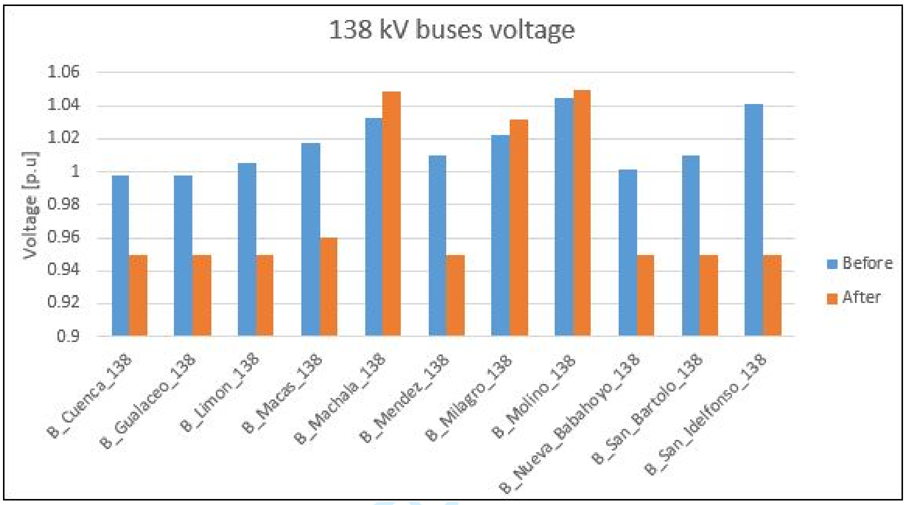

Figure 8. Peak demand Molino-Milagro 138 kV buses voltage before and after re-dispatch

230 kV rating

For most of the 230 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, but nevertheless all are within regulation levels as seen in Figure 9. Interestingly, angles change but stay within stability limits.

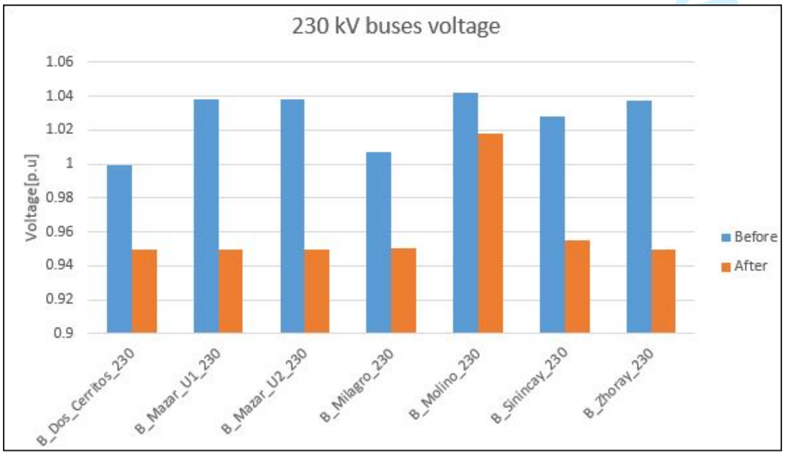

Figure 9. Peak demand Molino-Milagro 230 kV buses voltage before and after re-dispatch

Generators reactive power agency re-dispatch

Figure 10 shows the generator reactive power agency re-dispatch before and after performing the optimization. Paute generator increases whereas Mazar decreases the reactive power agency.

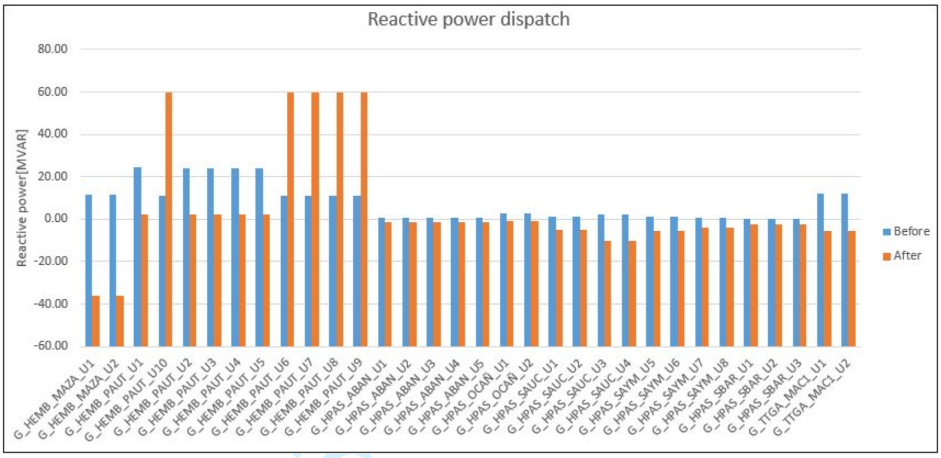

Figure 10. Peak demand Molino-Milagro generators reactive power agency before and after re-dispatch

Capacitor's agency re-dispatch

In the Molino-Milagro zone there are only capacitor banks in Cuenca buses, Dos Cerritos, and Machala, by optimizing the GAMS model does not consider them because voltages were within regulations. A location analysis of new capacitors agency is carried out. Figure 11 shows the amount of reactive power to be provided by new capacitors and where to place them to reduce losses in the system.

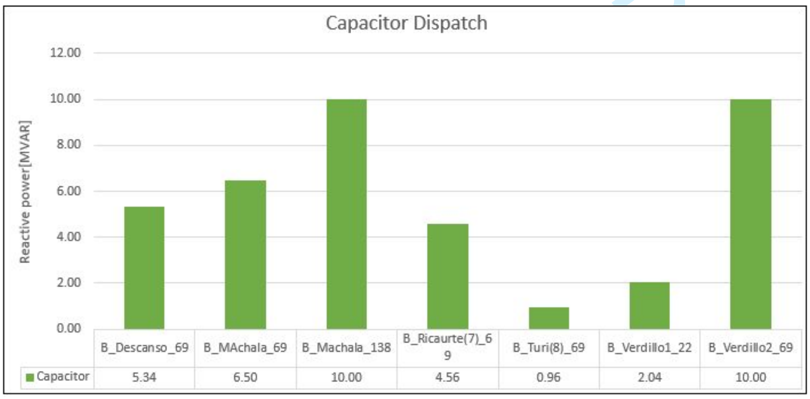

Figure 11. Peak demand Molino-Milagro capacitors agency re-dispatch

Losses

The total active power loss in the zone is computed subtracting the total active power generated minus the active power demanded by the connected loads. Figure 12 shows that the Molino-Milagro high demand loss are 12.3 MW, after optimization and applying the reactive power agency in the generators, loss is 9.1 MW i.e., a loss reduction of approximately 26%.

Figure 12. Peak demand Molino-Milagro Losses before and after of reactive power agency re-dispatch

Average Demand Molino-Milagro zone

69 kV rating

From Figure 13, there is an increase in the voltage levels after optimizing in most of the buses: Abanico, Arenal, Corpache, Los Cerezos, Nuevo Parque Industrial, SE11 Cuenca and Verdillo increased, whereas Alazan, Azogues, Cañar, Colectora Taday, Descanso, Lentaj, Macas, Machala, Milagro decreases, but all are within the regulation levels.

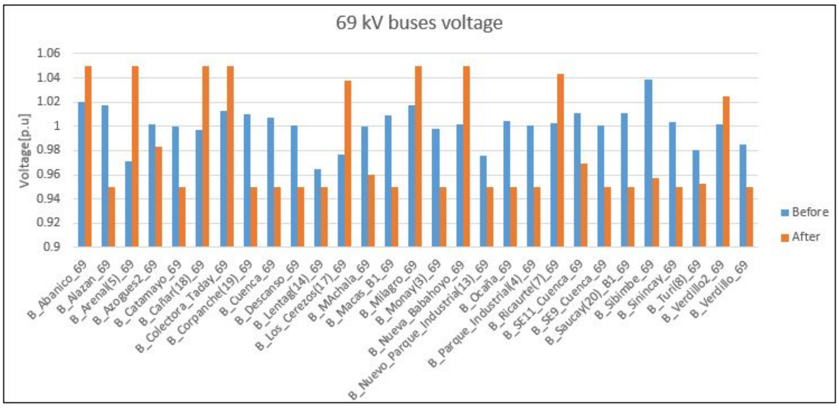

Figure 13. Average demand Molino-Milagro 69 kV buses voltage before and after re-dispatch

138 kV rating

For most of the 138 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, the buses most affected are Cuenca, Gualaceo, Macas, Machala, Mendez, Nueva Babahoyo and San Idelfonso, but nevertheless all are within regulation levels as seen in Figure 14.

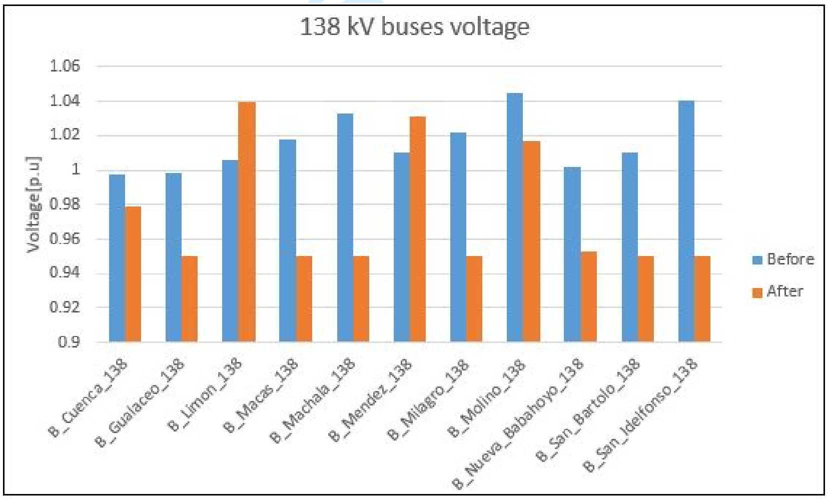

Figure 14. Average demand Molino-Milagro 138 kV buses voltage before and after re-dispatch}

230 kV rating

For most of the 230 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, except Molino bus, but nevertheless all are within regulation levels as seen in Figure 15.

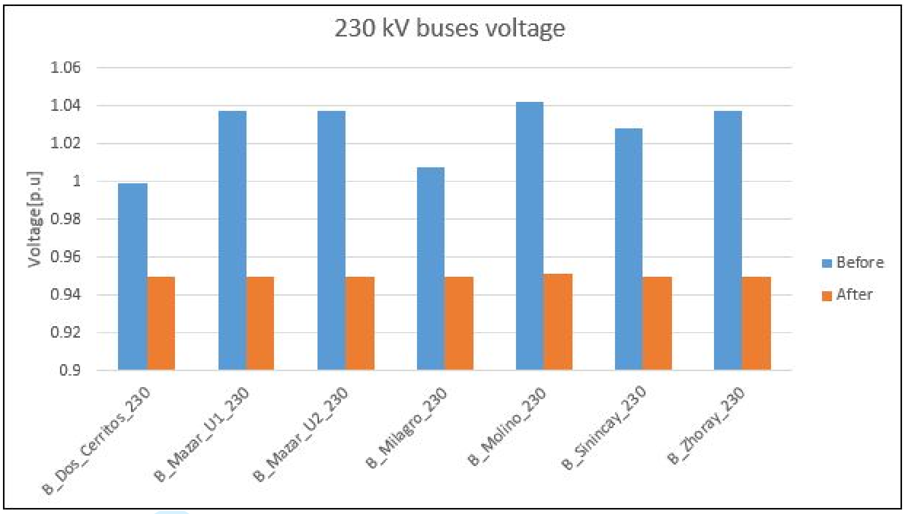

Figure 15. Average demand Molino-Milagro 230 kV buses voltage before and after re-dispatch

Generators reactive power agency re-dispatch

Figure 16 shows the generator reactive power agency re-dispatch before and after performing the optimization. Mazar drastically decreases the reactive power agency.

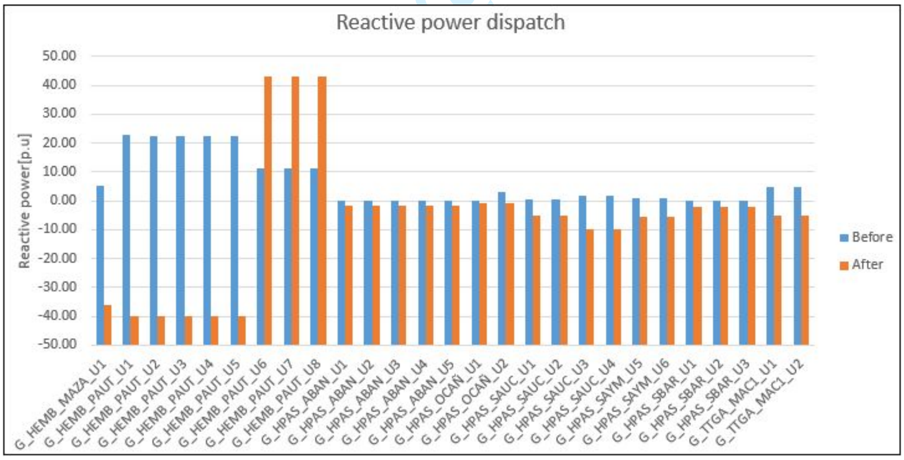

Figure 16. Average demand Molino-Milagro generators reactive power agency before and after re-dispatch

Capacitor's agency re-dispatch

In the Molino-Milagro zone there are only capacitor banks in Cuenca buses, Dos Cerritos and Machala, by optimizing the GAMS model does not consider them because voltages were within regulations. A location analysis of new capacitors agency is carried out. Figure 17 shows the amount of reactive power to be provided by new capacitors and where to place them to reduce losses in the system. Verdillo bus is the most need compensation.

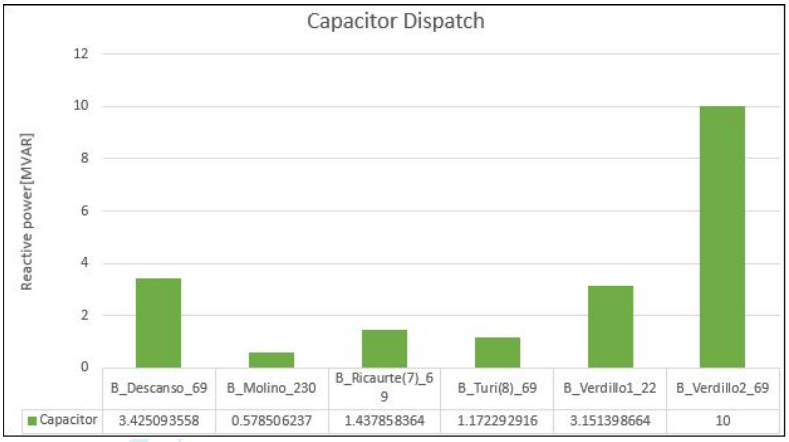

Figure 17. Average demand Molino-Milagro capacitors agency re-dispatch

Losses

The total active power loss in the zone is computed subtracting the total active power generated minus the active power demanded by the connected loads. Figure 18 shows that the Molino-Milagro average demand loss is 11.04 MW, after optimization and applying the reactive power agency in the generators, loss is 10.59 MW i.e., a loss reduction of approximately 4.07%.

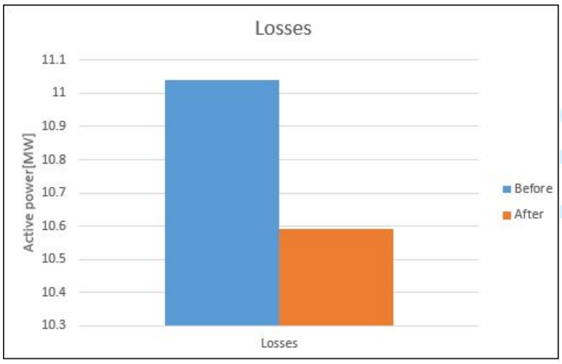

Figure 18. Average demand Molino-Milagro Losses before and after of reactive power agency re-dispatch

Minimum demand of Molino-Milagro zone

69kV rating

From Figure 19, there is an increase in the voltage levels after optimizing in most of the buses: Abanico, Arenal, Corpache, Los Cerezos, Nuevo Parque Industrial, SE_{11} Cuenca and Verdillo increased, while Alazan, Azogues, Cañar, Colectora Taday, Descanso, Lentaj, Macas, Machala, Milagro, and other voltages decreases, but all are within the regulation levels.

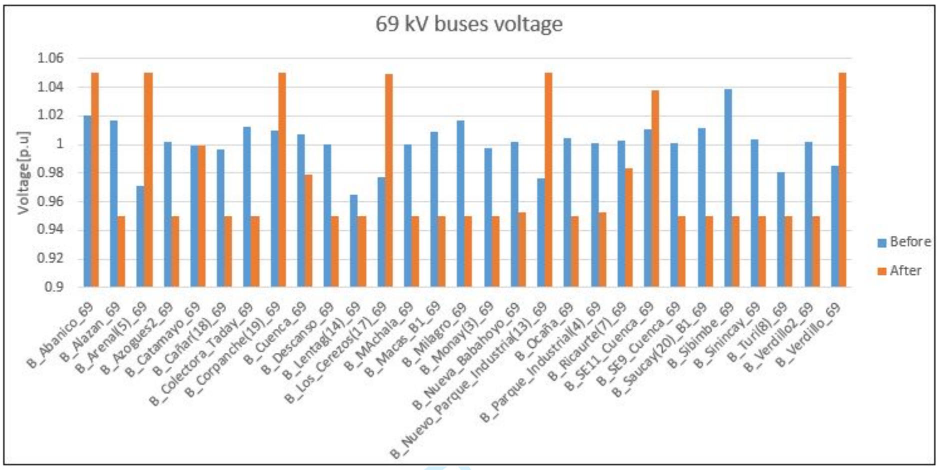

Figure 19. Minimum demand Molino-Milagro 69 kV buses voltage before and after re-dispatch

138 kV rating

For most of the 138 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, the buses most affected are Cuenca, Gualaceo, Limon, Macas, Machala, Mendez, Nueva Babahoyo and San Idelfonso, but nevertheless all are within regulation levels as seen in Figure 20.

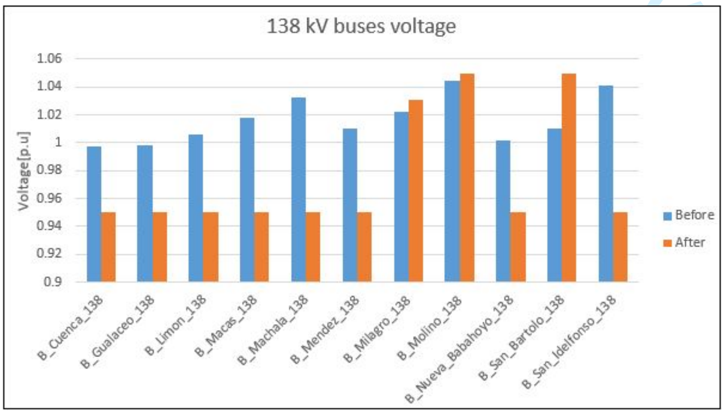

Figure 20. Minimum demand Molino-Milagro 138 kV buses voltage before and after re-dispatch

230 kV rating

For most of the 230 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, except Molino bus, but nevertheless all are within regulation levels as seen in Figure 21.

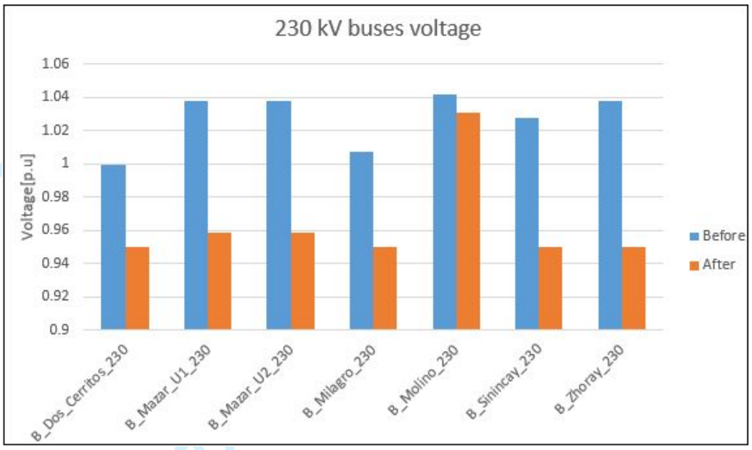

Figure 21. Minimum demand Molino-Milagro 230 kV buses voltage before and after re-dispatch

Generators reactive power agency re-dispatch

Figure 22 shows the generator reactive power agency re-dispatch before and after performing the optimization.

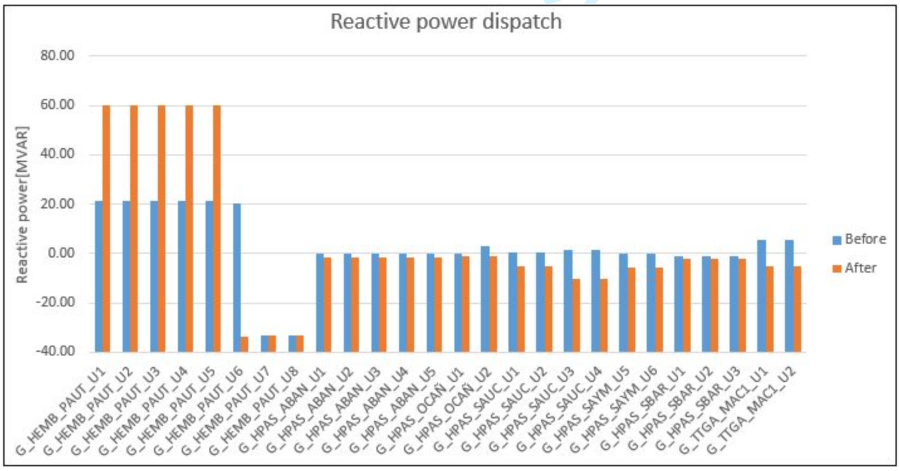

Figure 22. Minimum demand Molino-Milagro generators reactive power agency before and after re-dispatch

Capacitor's agency re-dispatch

In the Molino-Milagro zone there are only capacitor banks in Cuenca buses, Dos Cerritos, and Machala, by optimizing the GAMS model does not consider them because voltages were within regulations. A location analysis of new capacitors agency is carried out. Figure 23 shows the amount of reactive power to be provided by new capacitors and where to place them to reduce losses in the system. Verdillo bus is the most need compensation. Machala and Verdillo buses are most needed compensation.

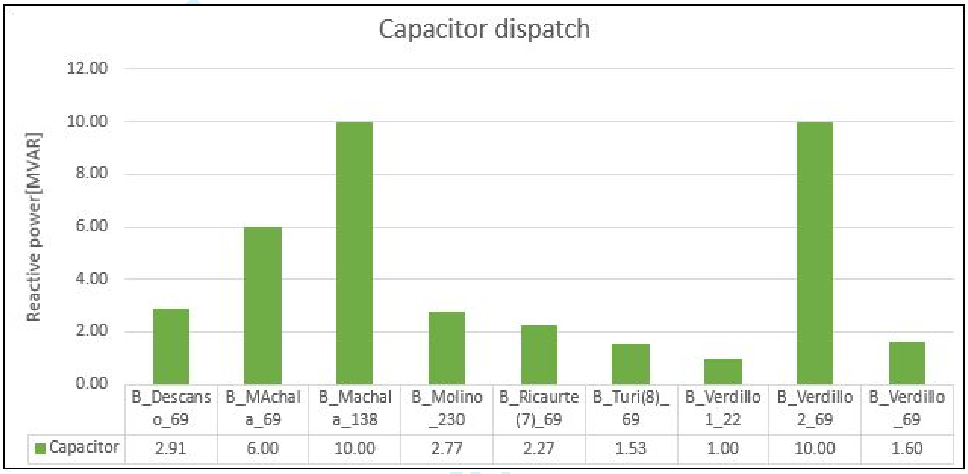

Figure 23. Minimum demand Molino-Milagro capacitors agency re-dispatch

Losses

The total active power loss in the zone is computed subtracting the total active power generated minus the active power demanded by the connected loads. Figure 24 shows that the Molino-Milagro average demand loss is 10.56 MW, after optimization and applying the reactive power agency in the generators, loss is 10.13 MW i.e., a loss reduction of approximately 4.07%.

Figure 24. Minimum demand Molino-Milagro Losses before and after of reactive power agency re-dispatch

High Demand Santa Rosa-Totoras zone

69 kV rating

From Figure 25, there is a change in the voltage levels after optimizing in most of the buses: Ambato, Ibarra, Mulalo and Riobamba increased, but they are all within levels and established regulations.

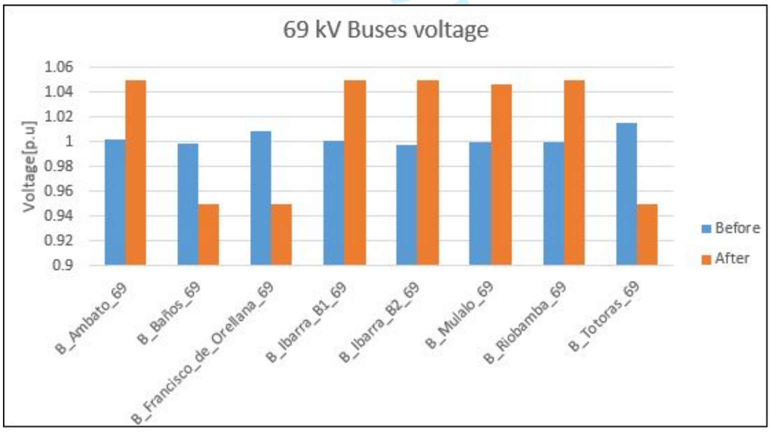

Figure 25. Peak demand Santa Rosa-Totoras 69 kV buses voltage before and after re-dispatch

138 kV rating

For most of the 138 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, the buses most are reduced: Cuenca, Gualaceo, Limon, Macas, Machala, Mendez, Nueva Babahoyo and San Idelfonso, but nevertheless all are within regulation levels as seen in Figure 26.

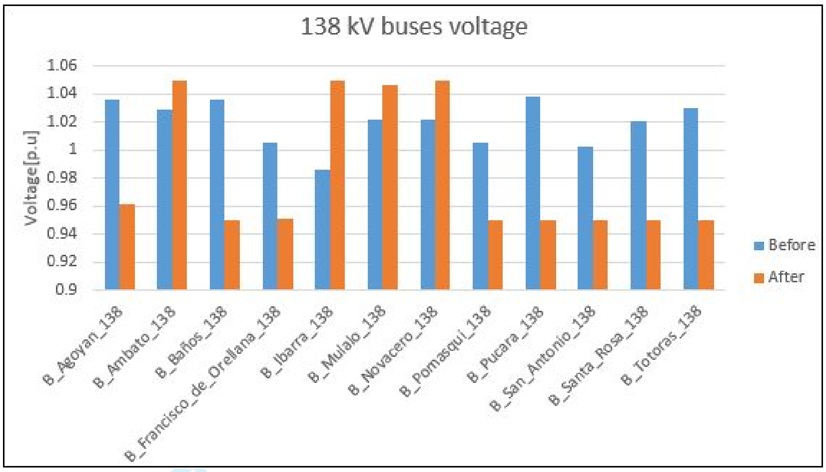

Figure 26. Peak demand Santa Rosa-Totoras 138 kV buses voltage before and after re-dispatch

230 kV rating

For most of the 230 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, but nevertheless all are within regulation levels as seen in Figure 27.

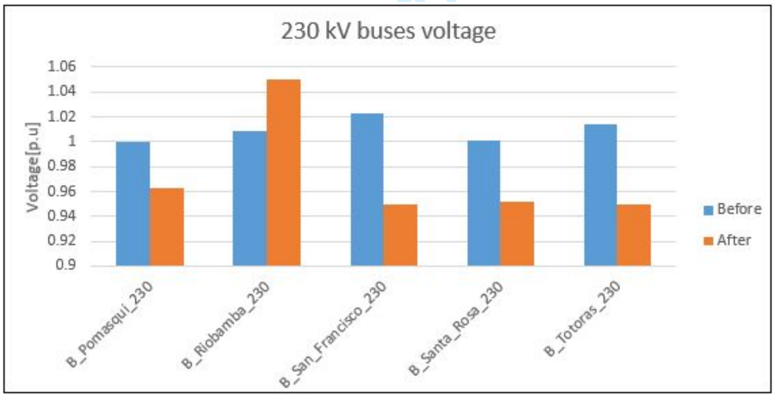

Figure 27. Peak demand Santa Rosa-Totoras 230 kV buses voltage before and after re-dispatch

Generators reactive power agency re-dispatch

Figure 28 shows the amount of reactive power to be provided by new capacitors and where to place them to reduce losses in the system. Agoyán and Santa Rosa increased production of reactive power compared to other generators in the area.

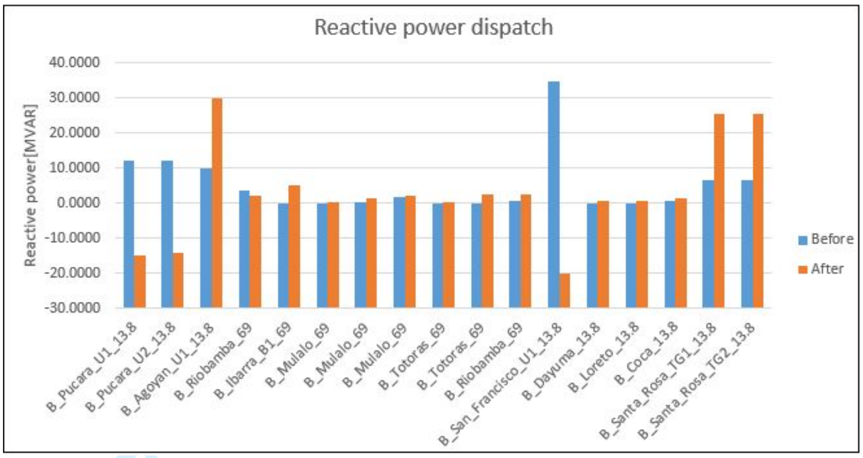

Figure 28. Before and after the reactive power dispatch area Santa Rosa-Totoras peak demand

Capacitor's agency re-dispatch

A location analysis of new capacitors agency is carried out. Figure 29 shows the amount of reactive power to be provided by new capacitors and where to place them in order to reduce losses in the system. Ambato bus is the most need compensation.

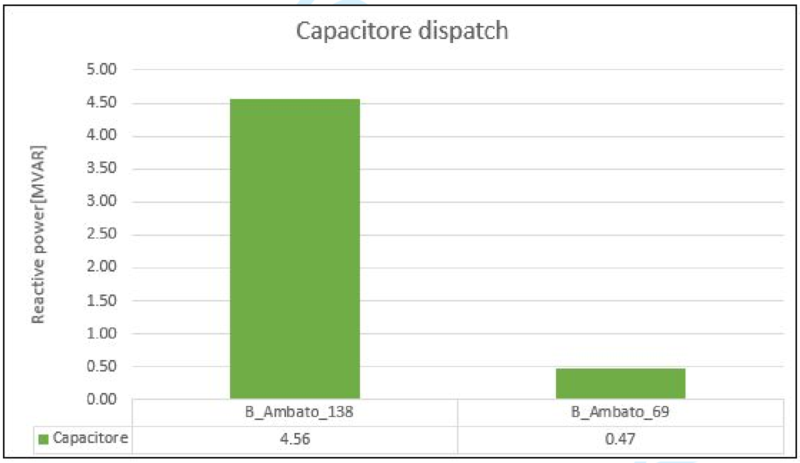

Figure 29. High demand Santa Rosa-Totoras capacitors agency re-dispatch

Losses

The total active power loss in the zone is computed subtracting the total active power generated minus the active power demanded by the connected loads. Figure 30 shows that the Molino-Milagro high demand loss are 11.5 MW, after optimization and applying the reactive power agency in the generators, loss is 9.8 MW i.e., a loss reduction of approximately 14.78%.

Figure 30. Peak demand Santa Rosa-Totoras losses before and after of reactive power agency re-dispatch

Average Demand of Santa Rosa-Totoras zone

69kV rating

From Figure 31, there is an increase in the voltage levels after optimizing in most of the buses: Ambato, Ibarra, Mulalo and Riobamba increases, but all are within the regulation levels.

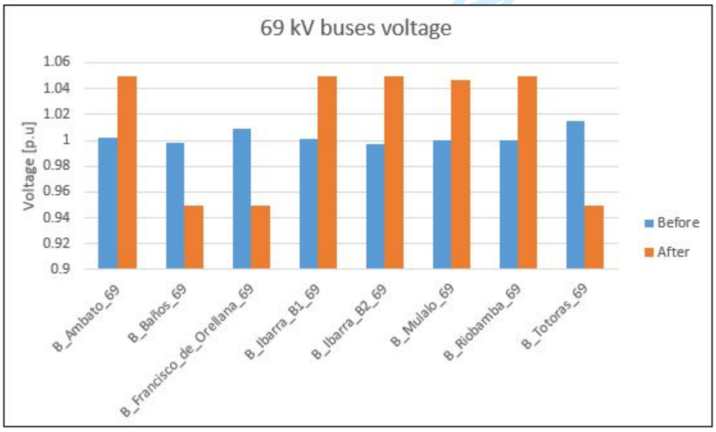

Figure 31. Average demand Santa Rosa-Totoras 69 kV buses voltage before and after re-dispatch

138 kV rating

For most of the 138 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, the buses most affected are Agoyán, Baños, Francisco de Orellana, Pomasqui, Pucara, San Antonio, Santa Rosa and Totoras, but nevertheless all are within regulation levels as seen in Figure 32.

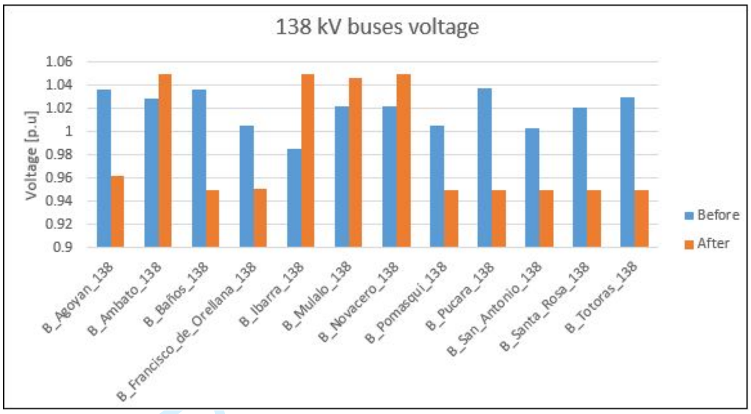

Figure 32. Average demand Santa Rosa-Totoras 138 kV buses voltage before and after re-dispatch

230 kV rating

For most of the 230 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, but nevertheless all are within regulation levels as seen in Figure 33.

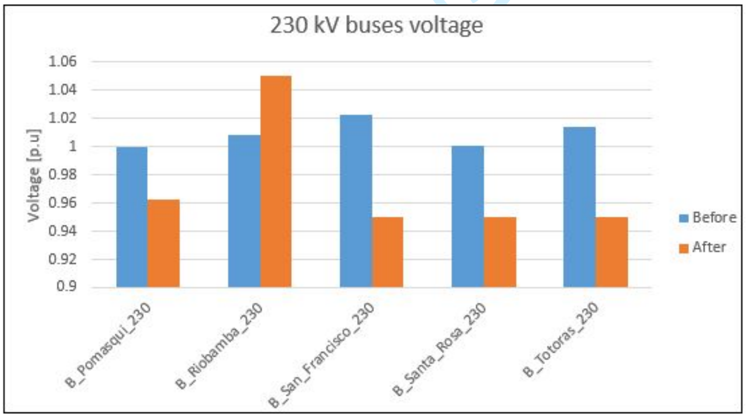

Figure 33. Average demand Santa Rosa-Totoras 230 kV buses voltage before and after re-dispatch

Generators reactive power agency re-dispatch

Figure 34 shows the generator reactive power agency re-dispatch before and after performing the optimization. Agoyán and Santa Rosa increased reactive power compared to other generators in the area.

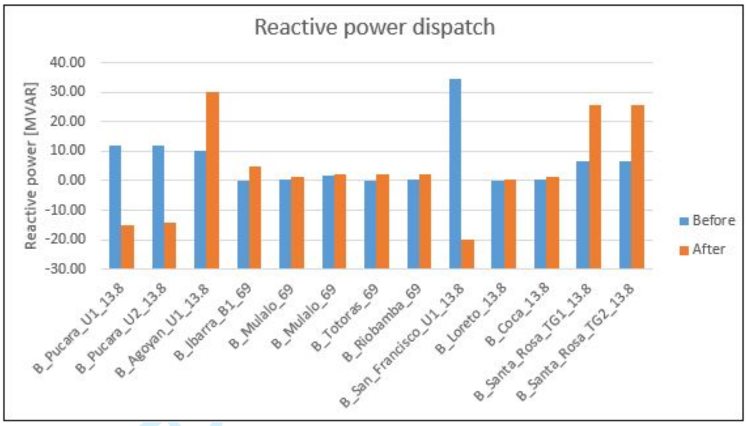

Figure 34. Average demand Santa Rosa-Totoras generators reactive power agency before and after re-dispatch

Losses

The total active power loss in the zone is computed subtracting the total active power generated minus the active power demanded by the connected loads. Figure 35 shows that the Molino-Milagro average demand loss is 10.22 MW, after optimization and applying the reactive power agency in the generators, loss is 9.5 MW i.e., a loss reduction of approximately 7.04%.

Figure 35. Average demand Santa Rosa-Totoras losses before and after of reactive power agency re-dispatch

Minimum demand for Santa Rosa-Totoras zone

69kV rating

From Figure 36, there is an increase in the voltage levels after optimizing in most of the buses: Ambato, Ibarra, Mulalo and Riobamba increased, but all are within the regulation levels.

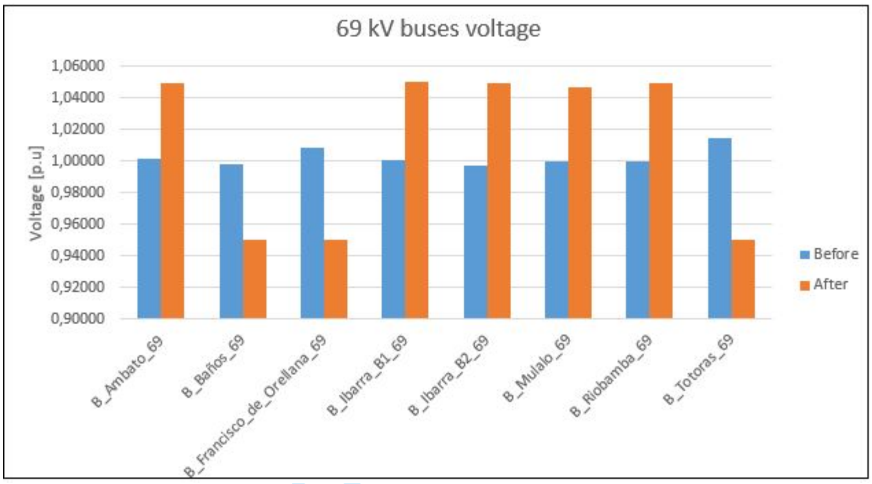

Figure 36. Minimum demand Santa Rosa-Totoras 69 kV buses voltage before and after re-dispatch

138 rating

For most of the 138 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, the buses most affected are Agoyán, Baños, Francisco de Orellana, Pomasqui, Pucara, San Antonio, Santa Rosa and Totoras, but nevertheless all are within regulation levels as seen in Figure 37.

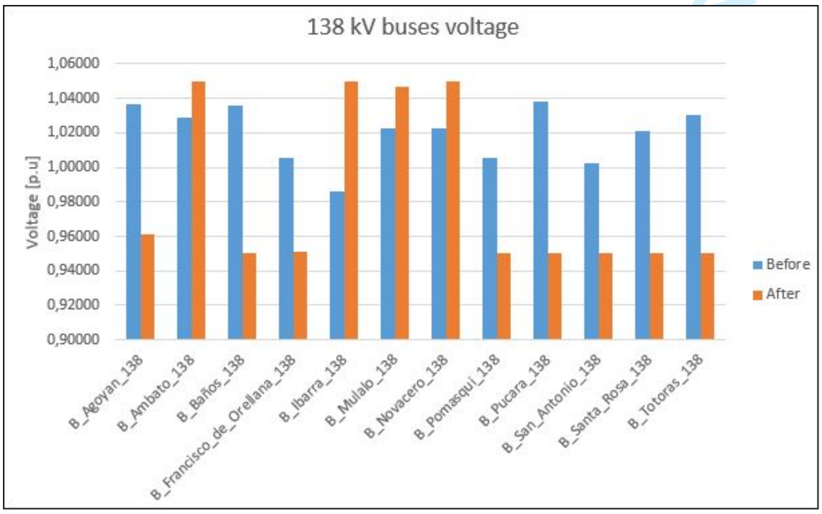

Figure 37. Minimum demand Santa Rosa-Totoras 138 kV buses voltage before and after re-dispatch

230 kV rating

For most of the 230 kV buses the opposite 69 kV behaviour occurs. Most of the voltages are reduced after performing the optimization re-dispatch, except Molino bus, but nevertheless all are within regulation levels as seen in Figure 38.

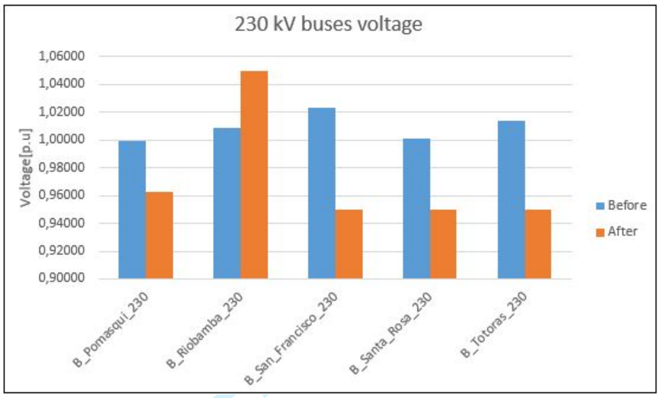

Figure 38. Minimum demand Molino-Milagro 230 kV buses voltage before and after re-dispatch

Generators reactive power agency re-dispatch

Figure 39 shows the generator reactive power agency re-dispatch before and after performing the optimization. The most significant changes are the Santa Rosa and Agoyán which increased production of reactive power whereas the San Francisco decreased production of reactive power compared to other generators in the area.

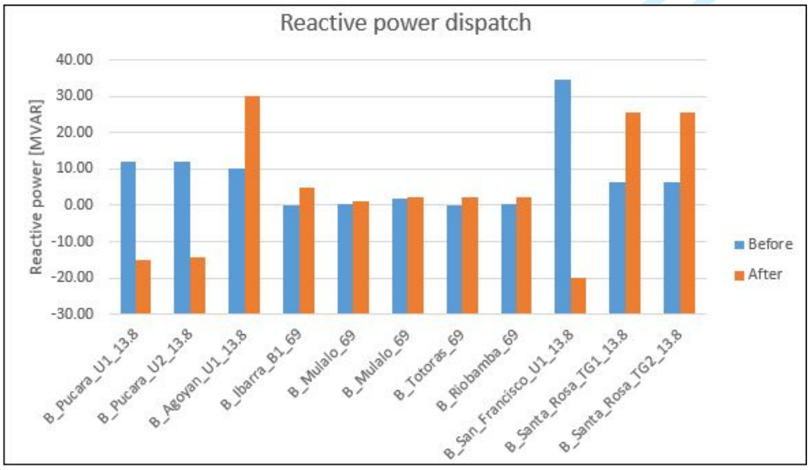

Figure 39. Minimum demand Santa Rosa-Totoras generators reactive power agency

Losses

The total active power loss in the zone is computed subtracting the total active power generated minus the active power demanded by the connected loads. Figure 40 shows that the Santa Rosa-Totoras average demand loss is 10.13 MW, after optimization and applying the reactive power agency in the generators, loss is 8.8 MW i.e., a loss reduction of approximately 4.55%.

Figure 40. Minimum demand Santa Rosa-Totoras losses before and after of reactive power agency re-dispatch

Discussion

The main transmission facilities of the NTG have been grouped into five operational zones: North, Northeast, Northwest, South and Southwest, North zone and south have the following operating restrictions: critical bus voltages, transformer overload, line overload.

This research aims at exploring the potential of semantic network structures as a form of co-created or shared knowledge to increase the effectiveness of reactive power re-dispatch, specifically in terms of interactivity between generation and passive reactive elements. These goals are achieved by explicitly representing the semantics of a certain knowledge domain and plotting networks of concepts and interrelationships. Separate tests were conducted on Molino-Milagro (a South subzone) and the Santa Rosa-Totoras (a North subzone) zones to corroborate the efficiency of the proposed method considering three possible ways of handling load demand: high, average, and minimum.

As the bus voltages are subjected to changes during load-flow and must be maintained within the upper and lower bounds, the voltage profile of all 69 kV buses in the case studies of peak, average and minimum demand were checked and found to be within the limits, as clearly indicated in Figures 7, 13 and 19, respectively for Molino-Milagro and Figures 25, 31 and 36 respectively for Santa Rosa-Totoras zone. Separate test were conducted for 138 kV buses when there is a maximum, average and minimum demand, voltage profile found to be within the limits, as clearly indicated in Molino-Milagro zone, Figures 8, 14 and 20, respectively and for the Santa Rosa-Totoras zone, Figures 26, 32 and 37. Finally, the voltages profile of all the 230 kV buses in the case studies of peak, average and minimum demand were checked and found to be within the limits, as clearly indicated in Figures 9, 15 and 21, respectively for the Molino-Milagro zone and Figures 27, 33 and 38, respectively for Santa Rosa-Totoras zone. The solutions appear to be optimal and feasible. Effective reactive power scheduling has become the need of the hour for maintaining system voltage stability.

The system data was organized in Microsoft Excel with the objective that GAMS take the data in matrix form according to rows and columns. Each node is assigned a number so that in the code written in GAMS can compare each bar and generate the own and mutual admittance matrices, also the assigned number helps us to know exactly in which node the generators and elements are connected liabilities of the system.

For the two proposed zones, the reactive power generated before and after performing the optimization was obtained for both maximum, average, minimum demand, whose data are found in Figures 10, 16, 22, 28, 34 and 39 respectively.

The method chosen to perform the model was non-linear programming. GAMS provides a varied number of solvers; this research looks for one that closely resembles the model. There are several methods which are either routed through global solutions or local solutions. The most efficient methods are those that find local solutions, the Bonmin solver was used to find the solutions to our problem. The most viable methods to solve the proposed objective are within the study of non-linear programming because the power flow equations are quadratic, this research uses Bonmin GAMS which resembles the model which it has equality and inequality restrictions. The most visible benefit is the reduction of active power losses through the re-dispatch of reactive power.

Conclusion

Notwithstanding the limitations, this study suggests that it is possible to integrate different data sources, and this has significant advantages in and of itself. The minimization of active power losses in the lines was carried out and at the same time the voltage profiles were maintained according to the regulations established by CONELEC in the two NTG areas studied. The solver that was used to solve the optimization problem in the GAMS tool, which is an open-source solver for mixed integer non-linear programming, which implements derivative approximative algorithms. The basis for a power flows optimization depends on the data provided by the network and its limitations or restrictions. The more the whole network is reduced, the less approximate results are obtained, so the largest possible number of elements must be considered and thus have more adequate results. Reducing the losses in the system implies having voltages in the limits of restriction in the buses so it must be put into the balance if we want to have a stable system or reduce losses and thus have economic savings. Finally, reconstruction of individual reactive power cognitions requires a profound and mutual understanding of the collaborators' perspectives and shared interpretations of the problem.

This study provides a framework for the exploration of reactive power dispatch at national level using general purpose tools. The framework developed within this study extends our knowledge by testing different reactive power measures and giving insights into national energy use. These insights will enable rational and considered responses to be formulated to the problems of integrating renewables into the generation portfolio that are likely to be faced in the future.

In summary, a reactive power dispatch optimization method that can be used by the system operator to centralize the scheduling of reactive power from generators has been proposed. Results show that centrally scheduling the reactive power outputs of the available generators, the bus voltages in the network can be maintained within the limits. GAMS finds a set of generator reactive power schedules that will maintain the bus voltages within acceptable limits and satisfy generator reactive power and power factor constraints. A piecewise-linear approximation of the generator's reactive power function is used in this research.

The methodology being proposed is an optimum dispatch formulation allows for a feasible solution, one generator is chosen as a regulating reserve (as a “slack” generator) to generate the power requirement for additional real power losses. Also, the change in voltage when connecting or disconnecting capacitor power banks capacitors or reactors, it should be less than 5% of the voltage nominal of the bus where the compensation is located.

In this research a solution is presented to improve voltage stability margin of power systems in a contingency condition based on reactive power generation dispatch of shunt capacitors along with active and reactive power generation dispatch of each unit.

With regards to the size of the network, which corresponds to the numbers of nodes and branches, the BONMIN solvers took more time and iterations to find the optimal solutions, i.e., for the allocation of a 69 kV grid, takes a higher number of iterations and high execution time than for the 138 kV or 230 kV. Iteration count and total execution times vary with the size of the network and the number and type o the reactive elements to be allocated. In the context of nonlinear problems with non-convex functions, exact solutions for large-scale problems are often impractical or unavailable. BONMIN's deterministic “branch-and-bound” decomposition algorithm has a convex optimal point.

BONMIN is a solver that looks for local optimums instead of a global solution. Figures in the paper shows this characteristic i.e., is a point where the function value is smaller than at nearby points, but possibly greater than at a distant point, i.e., the local optima found by Bonmin are quite good ones.

This study provides additional evidence with respect to reactive power dispatch that is potentially of significant value as a policy tool. It can be used to inform and direct policy by testing the effect that various policy decisions are likely to have on the reactive power dispatch. A key strength of the present study was that the framework will significantly increase our theoretical understanding of the complex inter-relationships that exist, not only between the various elements within the demand side of the Ecuadorian NTG, but also the generation side.

Finally, this study has shown first and foremost that the data set components are generally available in some form to many, if not all, countries. With all the data set in place the methodology used in this research is adequate.

References

CONELEC (2000). Procedimientos del Mercado Eléctrico Mayorista [Procedures of the wholesale electricity market]. MEER, http://www.regulacionelectrica.gob.ec/wp-content/uploads/downloads/2016/02/Regulacion-No.-CONELEC-007-00.pdf

ARCONEL (2022). Balance Nacional de Energía Eléctrica [National electric energy balance]. Technical report, MEER, https://www.controlrecursosyenergia.gob.ec/balance-nacional-de-energia-electrica/

Batzias, F. and Marcoulaki, E. (2002). Restructuring the keywords interface to enhance CAPE knowledge acquisition via an intelligent agent. Computer Aided Chemical Engineering 10: 829– 834, doi: 10.1016/S1570-7946(02)80166-3

Blackburn, J. and Domin, T. (2014). Protective Relaying: Principles and Applications. CRC Press.

Bonami, P. and Lee, J. (2007). Bonmin users' manual. Numer Math 4:1-32

Chen, C.-R., Lee, H.-S., and Tsai, W. (2005). On-line optimal shunt capacitors dispatch of peak power systems. In 2005 IEEE/PES Transmission and Distribution Conference and Exposition: Asia and Pacific, pages 1–4, doi: 10.1109/TDC.2005.1547070

Cohen, M. S., Rissman, J., Suthana, N. A., Castel, A. D., and Knowlton, B. J. (2016). Effects of aging on value-directed modulation of semantic network activity during verbal learning. NeuroImage, 125:1046–1062, doi: 10.1016/j.neuroimage.2015.07.079.

Gómez-Expósito, A., Conejo, A., and Cañizares, C. (2018). Electric Energy Systems: Analysis and Operation. CRC Press.

Grainger, J. and Stevenson, W. (1994). Power System Analysis. McGraw-Hill.

Hindi, K. and Ab Ghani, M. (1991). Dynamic economic dispatch for large scale power systems: a lagrangian relaxation approach. International Journal of Electrical Power and Energy Systems, 13(1):51–56, doi: 10.1016/0142-0615(91)90018-Q

Khan, J., Hardas, M., and Ma, Y. (2005). A study of problem difficulty evaluation for semantic network ontology based intelligent courseware sharing. In The 2005 IEEE/WIC/ACM International Conference on Web Intelligence (WI'05), pages 426–429, doi: 10.1109/WI.2005.15

Lehmann, F. (1992). Semantic networks. Computers and Mathematics with Applications, 23(2):1–50, doi: 10.1016/0898-1221(92)90135-5

Maida, A. S. and Shapiro, S. C. (1982). Intensional concepts in propositional semantic networks. Cognitive Science, 6(4):291–330, doi: 10.1016/S0364-0213(82)80007-4

McIntosh, A. R. (2000). Towards a network theory of cognition. Neural Networks, 13(8):861–870, doi: 10.1016/S0893-6080(00)00059-9

MEER (2017). Plan Maestro de Electricidad 2018-2027 [Electricity Master Plan 2018 - 2027], MEER https://www.cnelep.gob.ec/wp-content/uploads/2020/01/Plan-Maestro-de-Electricidad-2018-2027.pdf

Rayudu, K., Yesuratnam, G., and Jayalaxmi, A. (2016). Improving voltage stability by optimal reactive power dispatch based on genetic algorithm and linear programming technique. In 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), pages 1357–1362, doi: 10.1109/ICEEOT.2016.7754904

Rewienski, M. and White, J. (2006). Model order reduction for nonlinear dynamical systems based on trajectory piecewise-linear approximations. Linear Algebra and its Applications, 415(2):426–454. Special Issue on Order Reduction of Large-Scale Systems, doi: 10.1016/j.laa.2003.11.034

Santos, G., Pinto, T., Vale, Z., Morais, H., and Praca, I. (2013). MASCEM restructuring: Ontologies for scenarios generation in power systems simulators. In 2013 IEEE Power Energy Society General Meeting, pages 1–5, doi: 10.1109/PESMG.2013.6672916

Seifi, H. and Sepasian, M. (2011). Electric Power System Planning. Issues, Algorithms and Solutions. Springer.

Sowa, J. F. (2014). Principles of Semantic Networks: Explorations in the Representation of Knowledge. Morgan Kaufmann.

Surender Reddy, S., Abhyankar, A.R. and Bijwe, P.R. (2011) Reactive power price clearing using multi-objective optimization. Energy (36)5 pages (3579-3589). doi:10.1016/j.energy.2011.03.070.

Transelectric (2020). Plan de Expansión de la Transmisión [Transmission Expansion Plan]. Recursos y Energía. https://www.recursosyenergia.gob.ec/wp-content/uploads/2020/01/5.-PLAN-DE-EXPANSION-DE-LA-TRANSMISION.pdf

Xia, X. and Elaiw, A. (2010). Optimal dynamic economic dispatch of generation: A review. Electric Power Systems Research, 80(8):975–986, doi: 10.1016/j.epsr.2009.12.012

Zhao, B., Guo, C., and Cao, Y. (2005). A multiagent-based particle swarm optimization approach for optimal reactive power dispatch. IEEE Transactions on Power Systems, 20(2):1070–1078, doi:10.1109/TPWRS.2005.846064