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OPTIMAL LOCATION OF REGULATING TRANSFORMER TAPS TO MINIMIZE LOSSES IN THE ELECTRICAL SYSTEM

UBICACIÓN ÓPTIMA DE LAS TOMAS DE REGULACIÓN DEL TRANSFORMADOR PARA MINIMIZAR PÉRDIDAS EN EL SISTEMA ELÉCTRICO

Topa-Caseres Walter Fabián [1]; Quinatoa Carlos [2]; Ortiz Josué [3]

[1] Technical University of Cotopaxi. Latacunga, Ecuador. Correo: walter.topa9134@utc.edu.ec.

[2] Technical University of Cotopaxi. Latacunga, Ecuador.
Correo: carlos.quinatoa7864@utc.edu.ec.

[3] Japan University Institute. Quito, Ecuador. Correo: jortiz@itsjapon.edu.ec.

Abstract

The electric power system have lines, reactor, regulator voltage, transformer regulator and other elements. These are necessary to carry the energy towards demand electric. The system operate with dispatch economic (DE) where it has the objective function and constrains. However, they DE do not necessary include the minimization power losses that are very import because reduce operation cost. Therefore, in this paper it is realize an optimal location of regulating transformer taps to minimize losses in the electrical system using convex optimization in power flow equations. For this suppose, it take account the bus injection model where it obtain all equations necessary. Then, the model propose are implemented with IEEE 14 bust system test as validation between Digsilent Power Factory and the model implement is of the system electric of Quito city in Ecuador. The result of minimizing lose in optimization process is 0.11 MW.

Palabras clave: Optimization, nonlinear, power flow, loss electric, transformer, regulator.

Resumen

El sistema eléctrico de potencia cuenta con líneas, reactancia, regulador de voltaje, transformador regulador y otros elementos. Estos son necesarios para llevar la energía hacia la demanda eléctrica. El sistema opera con despacho económico (DE) donde tiene la función objetivo y restricciones. Sin embargo, los DE no necesariamente incluyen la minimización de pérdidas de potencia que son muy importantes porque reducen el costo de operación. Por lo tanto, en este documento se realiza una ubicación óptima de las tomas de regulación del transformador para minimizar las pérdidas en el sistema eléctrico utilizando la optimización convexa en las ecuaciones de flujo de potencia. Para este supuesto, se toma en cuenta el modelo de inyección de bus donde se obtienen todas las ecuaciones necesarias. Luego, el modelo propuesto se implementa con la prueba del sistema de bus IEEE 14 como validación entre Digsilent Power Factory y el modelo implementado es del sistema eléctrico de la ciudad de Quito en Ecuador. El resultado de minimizar la pérdida en el proceso de optimización es de 0,11 MW.

Keywords: Optimización, no lineal, flujo de potencia, pérdida eléctrica, transformador, regulador.

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1. Introduction

The strategic positioning of taps within transformers is critical to maintain voltage regulation and improve system stability in power distribution networks. A multitude of academic papers propose various methodologies to identify the most suitable plug configuration for transformers [1]. One approach involves using a genetic algorithm to inte- grate variable transformer inputs into reactive power pric- ing models, which reduces the overall costs associated with reactive power while increasing system reliability. Another methodology conceptualizes tap position adjustment as a Markov decision process, which leverages reinforcement learning algorithms to reduce voltage discrepancies within the system [2], proving effective in numerical simulations related to power supply distribution testing. Furthermore, it is advisable to refine the evolutionary strategy aimed at determining the optimal plug arrangement for off-line distribution transformers [3], taking into account seasonal variations and the impact of distributed energy resources on voltage constraints, by complementing it with Monte Carlo simulations that validate the effectiveness of the proposed algorithm in real power distribution networks [4].

It is essential to establish the ideal position of taps in regulating transformers to reduce energy losses. It is necessary to incorporate state-of-the-art technologies and techniques such as genetic algorithms, reinforced learning and simulations to increase the efficiency and stability of the power system. The location of taps in regulating transformers causes considerable energy losses in electrical systems. It is essential to improve their position in order to reduce operational costs and enhance energy efficiency, taking into account seasonal variations and distributed resources. To mitigate energy losses in power systems, several transformer technologies can be implemented. Amorphous core transformers use an amorphous metal alloy core, which significantly reduces energy losses due to their minimal core losses and high magnetic perme- ability, making them exceptionally efficient [5]. Similarly, nanocrystalline core transformers take advantage of a nanocrystalline structure to reduce core losses and improve efficiency, which further contributes to reducing losses in power systems [6]. High temperature superconductors (HTS) also present a very promising alternative as they exhibit zero electrical resistance at elevated temperatures, which minimizes power losses when incorporated into transformers [7], [8]. In addition, ferrite core transformers are recognized for their low core losses and high magnetic permeability, making them a predominant choice for en- ergy efficient systems. Finally, transformers equipped with power factor correction (PFC) are specifically designed to improve power factor and decrease power losses, thus increasing overall system efficiency [9].

The optimization of variable transformer taps using the genetic algorithm in the pricing method decreases the reactive power cost by employing transformer taps as a control variable. In addition, the improvement of trans- former inputs increases system protection and decreases end-user costs [10]. In contrast, a batch reinforcement learning algorithm improves the tap arrangement through a linear power flow model to calculate the voltage in- tensity. This method reduces voltage variation in power distribution systems, and its effectiveness has been proven through numerical simulations on IEEE test feeders [11]. In addition, an evolution strategy is used to establish the ideal configuration of the taps as a function of the average load. Monte Carlo simulations analyze the possibility of violating voltage constraints after optimization, ensuring that the configuration adheres to voltage regulations [12]. The ideal taps configuration for distribution transformers was practically established, achieving acceptable results in tests with real feeders [13].

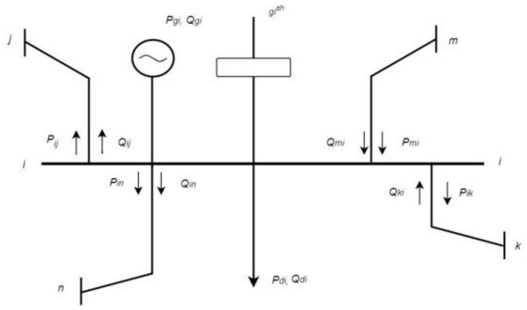
Optimal placement of transformer regulating tap chang- ers is crucial for reducing energy losses in power systems. By strategically deploying transformer tap changers, utili- ties can significantly reduce energy waste while maintain- ing efficient power transfer [14]. The operational capability of transformer tap changers enables real-time adjustment of voltage levels, which improves system efficiency [15]. In addition, the architecture of regulating transformers incorporating integrated tap changers streamlines these adjustments and makes them vital for minimizing energy losses [15]. Performing power flow analysis helps identify regions where significant power losses occur, allowing utili- ties to optimize their systems effectively [16] Implementing these methodologies, along with other loss reduction strategies such as optimizing transformer design and using advanced materials, can significantly reduce operating costs and impact the environment [17]. Therefore, the optimal placement of transformer regulating tap changers is a critical element in achieving an efficient electrical sys- tem [17]. Establish the ideal position of taps in regulating transformers to reduce energy losses in electrical systems, through the implementation of sophisticated techniques and novel technologies, optimizing energy efficiency and distribution system stability.

2. Formulation of the problem

A. Bus injection model

The bus injection model is fundamental and necessary understand because it this can be modeling the power flow and optimization problem equations. In the Fig. 1, it can see all elements that connected this bus.

Fig. 1. *Bus Injection Model*



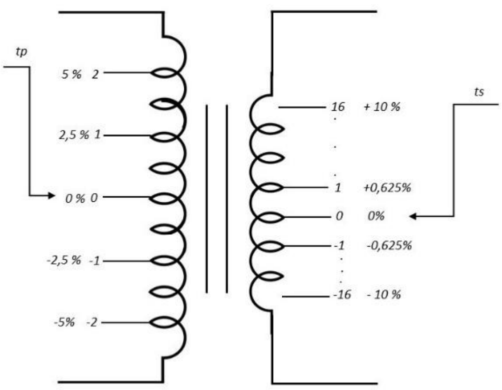
B. Transformer

The transformer is element important for transmission of energy from generation to load, it changing of voltage level. In the sub-transmission and transmission system these transformers have OLTC in of primary and sec- ondary winding.

- t_p.-In the primary winding for each tap step the n_i increases or decreases 2.5 %.
- t_s.- In the secondary winding for each tap step n_j increases or decreases 0.625 %.

In generally the auto-transformer substation in the primary winding tp has five step tap ± 5% and the secondary winding has thirty-three step tap ± 10%. The Fig.2 show the tap.

Fig. 2. *Auto Transformer*



The tap help system to regulation voltage and it is variable integer into the optimization problem.

C. Models and their equivalence

The power flow are necessary to observe the state system in the system and it diagnose that operate correctly. Therefore, it is important include the on-load tap chargers (OLTC) in the power transformer whit it objective of voltage regulation for it minimizing the loses through optimal location Taps and into of power flow equations. Accordingly, we present the following nonlinear model, which is defined as:

$$\min z = g_{ii}\; n_j^2 v_i + n_i^2 v_i - 2 v_i vj \cos(\vartheta i - \vartheta j) \quad (1)$$

$$Pg_i + gsh_i v^2 - Pd_i - \sum_{ij \in N L} P_{ij} - \sum_{ij \in N L} P_{ji} = 0 \quad (2)$$

$$Qg_i + bsh_i v^2 - Qd_i - \sum_{ij \in N L} Q_{ij} - \sum_{ij \in N L} Q_{ji} = 0 \quad (3)$$

$$P_{ij} = g_{ij} n_j^2 vi^2 - g_{ij} n_i n_j vivj \cos(\vartheta_i - \vartheta_j) + b_{ij} n_i n_j vivj \sin(\vartheta_i - \vartheta_j) \quad (4)$$

$$P_{ji} = g_{ij} n_i^2 vj^2 - g_{ij} n_i n_j vivj \cos(\vartheta_i - \vartheta_j) - b_{ij} n_i n_j vivj \sin(\vartheta_i - \vartheta_j) \quad (5)$$

$$Q_{ij} = b_{ij} n_j^2 vi^2 - b_{ij} n_i n_j vivj \cos(\vartheta_i - \vartheta_j) - g_{ij} n_i n_j vivj \sin(\vartheta_i - \vartheta_j) \quad (6)$$

$$Q_{ji} = b_{ij} n_i^2 vj^2 - b_{ij} n_i n_j vivj \cos(\vartheta_i - \vartheta_j) + g_{ij} n_i n_j vivj \sin(\vartheta_i - \vartheta_j) \quad (7)$$

$$n_i = np_{nom} + tp * 0.025 \quad (8)$$

$$n_j = ns_{nom} + ts * 0.00625 \quad (9)$$

$$\vartheta_{min} \leq \vartheta_i \leq \vartheta_{max} \quad (10)$$

$$v_{min} \leq v_i \leq v_{max} \quad (11)$$

$$Pg_{min} \leq Pg_i \leq Pg_{max} \quad (12)$$

$$Qg_{min} \leq Qg_i \leq Qg_{max} \quad (13)$$

The equation (1) is the objective function that represent the minimum loses of the network and it is nonlinear, the equations (2) and (3) are power balance constraints and it represent bus injection model, the equations (4) and (5) are the power flow active and reactive from i to j and it is nonlinear, the equations (6) and (7) are the power flow active and reactive from j to i and it is nonlinear. The equation (8) is number of turns of the primary winding transformer, the equation (9) is number of turns of the secondary winding transformer.

The equation (10) is the constraint of angle of nodes of system.

The equation (11) is the constraint of voltage of nodes of system. The equation (12) and (13) are the constraints of active and reactive power generation the nodes of system. The variables t_p and t_s are integers that they represent steps of primary an secondary transformer

D. Problem

The model optimization presented previous is hard to solve, because it is nonlinear mixed integer problem. The function objectives is nonlinear. The term cos and they variables vi, vj, θi, θj, ni and nj increase the complexity of problem. The equations (4) - (7) are balance active and reactive power are nonlinear and finally the equation (8) and (9) are lineal integer for the variable tp and ts.

In the literature, there are two form for solve this problem:

- Meta-heuristic
- Convex optimization

Metaheuristics is an optimization methodology that seeks to find approximate solutions to complex problems where exact methods are ineffective. These techniques, such as genetic algorithms, simulated annealing and parti- cle swarming, are especially useful in problems with large, nonlinear search spaces. Metaheuristics work by exploring and exploiting the solution space intelligently, seeking a balance between global exploration and local exploitation.

Their main advantage is the ability to find good quality solutions in a reasonable time, being applicable in fields such as engineering. The main problem with metaheuristics is their dependence on specific parameters and the lack of global optimality guarantee.

Convex optimization is a sub-discipline of mathematical optimization that focuses on problems where the objective function and constraints are convex. In these problems, any linear combination of points within the domain also belongs to the domain, and any local minimum is also a global minimum. Convex optimization is fundamental because many real-world problems, such as cost minimization, profit maximization, and system design, can be modeled in this way.

Furthermore, efficient algorithms exist for solving convex problems, which guarantees optimal and robust solutions in fields such as economics, engineering and machine learning.

3. Model Solution

For to address the model optimization nonlineal mixed integer and special the previous problem. In this paper take of account convex optimization due they have several advantage with respect meta-heuristic. Into the problem relation are: Hyperbolic cone, semidefinite programming, second order cone programming, linear programming, quadratic programming and others. In this case only use the second order order cone programming. If we define the new variables using trigonometric function such as:

$$x_i = V_i^2 \cos(\vartheta^2) \quad (14)$$

$$y_i = V^2 \sin(\vartheta^2) \quad (15)$$

equations (14) and (15) are represented in Cartesian form as follows:

$$|V_i|^2 = x_i + b_i \quad (16)$$

For the transmission line i to j the equation is following:

$$x_{ij} = V_i V_j \cos(\vartheta_i - \vartheta_j) \quad (17)$$

we define the following variable:

$$c_{ij} = V_i \cos(\vartheta_i) V_j \sin(\vartheta_j) \quad (18)$$

$$c_{ji} = V_j \cos(\vartheta_j) V_i \sin(\vartheta_i) \quad (19)$$

with the previous equation. We can write the following:

$$V_i V_j \sin(\vartheta_j - \vartheta_i) = c_{ji} - c_{ij} \quad (20)$$

If we take the equations 17 to 20 and it change the variable in equations a to 7. We have the following:

$$P_{ij} = (x_i - y_i) g_{ij} n^2{}_j - (x_{ij} - y_{ij}) g_{ij} n_i n_j + (c_{ji} - c_{ij}) b_{ij} n_i n_j \quad (21)$$

$$P_{ji} = (x_j - y_j) g_{ij} n_i^2 - (x_{ij} - y_{ij}) g_{ij} n_i n_j - (c_{ji} - c_{ij}) b_{ij} n_i n_j \quad (22)$$

$$Q_{ij} = (x_i - y_i) b_{ij} n_j^2 - (x_{ij} - y_{ij}) b_{ij} n_i n_j - (c_{ji} - c_{ij}) g_{ij} n_i n_j \quad (23)$$

$$Q_{ji} = (x_j - y_j) b_{ij} n_i^2 - (x_{ij} - y_{ij}) b_{ij} n_i n_j + (c_{ji} - c_{ij}) g_{ij} n_i n_j \quad (24)$$

The voltage magnitude constraints 11 can be changed accordingly then with the new introduced variables.

$$V_{imin}^2 \leq x_i + y_i \leq V_{imax}^2 \quad (25)$$

The power constraints can be modified:

$$|P_{ij}| \leq P_{ijmax} \quad (26)$$

$$|P_{ji}| \leq P_{jimax} \quad (27)$$

$$|Q_{ij}| \leq Q_{ijmax} \quad (28)$$

$$|Q_{ji}| \leq Q_{jimax} \quad (29)$$

Besides, the new variables 14 to 15 and 17 to 19 have the following relations:

$$c_{ij}^2 = x_i y_j \quad (30)$$

$$c_{ji}^2 = x_j y_i \quad (31)$$

$$x_{ij}^2 + (c_{ij} - c_{ji})^2 = (x_i + y_i)(x_j + yj) \quad (32)$$

and, finally the equations 30 to 32, we introduce the second order cone programming relaxations he to make these be convex inequality constraints. We transform the equality sign into inequality sign and present them into a 2-norm format to ensure the convexity.

$$\left\| \begin{matrix} 2c_{ij} \\ x_i - y_j \end{matrix} \right\| \leq x_i + b_j \quad (33)$$

$$\left\| \begin{matrix} 2c_{ji} \\ x_j - y_i \end{matrix} \right\| \leq x_j + b_i \quad (34)$$

$$\left\| \begin{matrix} 2x_{ji} \\ 2(c_{ij} - c_{ji}) \\ x_i - x_j + y_i - y_j \end{matrix} \right\| \leq x_i + x_j + y_i + y_j \quad (35)$$

Therefore, the load flow optimizations problem can be summarized as:

as:

$$\min z = \sum_{ij} P_{ij} + \sum_{ji} P_{ji} \quad (36)$$

Subject to:

$$(2), (3), (8), (9), (12), (13), (21) - (24), (25), (33) - (35) \quad (37)$$

4. Validation

The validation of model propose it take account the following assumptions:

- The primary Tap's can controller the voltage or power active and reactive.
- The secondary Tap's can controller the voltage or power active and reactive.
- The bus voltage can variate +- 10% of 1 per unit (0.90 a 1.10)
- The numbers of primary and secondary Tap's is the same Fig. 2.

If the primary Tap's are controller the voltage the secondary Tap's must not controller voltage, the same in the other case. This conditions is typical operation real life in the power system. The IEEE 14 bus system is reference for it validation of model, the data it found here [18]. The active power loses in normal conditional is 13.38 MW.

The methodology previous is implement in Gams using knitro solver and it also Digsilent 2021 the active power loses is 13.31 MW.

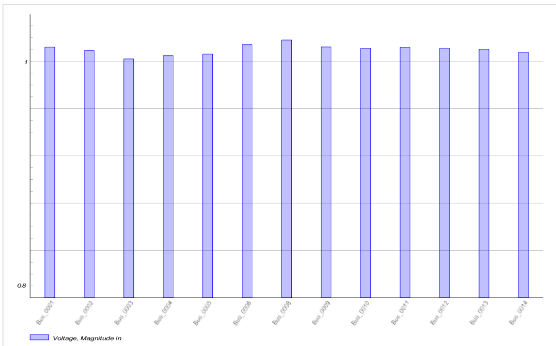
Nevertheless, the reduction is 0.07 MW. The TAP's position are the following:

Table 1. *Validation de TAP's and GAMS y DIGSILENT*

Names	Gams		Digsilent	
	Tap 1	Tap 2	Tap 1	Tap 2
Trf-05-06	0	12	0	12
Trf-04-09	0	5	0	5
3-Auto-Trf	-2	0	-2	0

The voltage magnitude in the process optimization is the following:

Fig. 3. *Voltage magnitude*



The bus voltage the fig 3 meet into constrains of optimization model. Whit the propose model validation with it digsilent, we model is well definite.

5. Results

The electric system to obtain the result is all circuit electric Quito, the data for modeling all the system are obtain National Electricity Operator (CENACE). These have 146 buses, the voltages 138 kV, 110 kV, 69 kV, 46 kV, 23 kV, 13.8 kV, 13.2 kV. The total loses of the system take account the TAP´s in the 0 positions is 8.86 MW. Also, the system have auto-transformers and two winding transformers.

The assumptions are te following:

- The auto-transformers have five TAP´S in the primary and the thirty two TAP´s in the secondary. The step are 2.5% and 0.625% respectively.
- The two winding transformers has eight step with 2.5% in the primary and the secondary winding do not has TAP´s.
- The limit voltage up and low is 1.05 and 0.95 by bus.
- The angle voltage is −π/2 and π/2

The limit voltages and angles help meet the stability of voltage in all system. The optimal location TAP´s of auto- transformer, we can observe the following table:

***Table 2.** Optimal location auto-transformer TAP´s*

Names	Gams		Digsilent	
	Tap 1	Tap 2	Tap 1	Tap 2
T_VICE_T2	0	0	0	0
T_VICE_T1	0	0	0	0
T_SROS_TRP	0	1	0	1
T_SROS_TRN	0	3	0	3
T_P.V.M	0	0	0	0
T_LOS_BNCS	3	0	3	0
T_BARRNVO_3D	0	0	0	0
T2_SALE_SAL	0	0	0	0
T1_SALE_SAL	0	0	0	0
T1_COTO_COT	0	1	0	1

The optimal location TAP´s of two winding transformer are the following:

***Table 3.** Optimal location two winding transformer TAP´s*

Names	Gams		Digsilent	
	Tap 1	Tap 2	Tap 1	Tap 2
T_CUMB_U1_U4	3	0	3	0
T_Chalpi_Grande	3	0	3	0
T_EEQ_3T0	3	0	3	0
T_GHER_U1_U6	3	0	3	0
T_HGUANG_U1_U5	3	0	3	0
T_HGUA_U6	3	0	3	0
T_Magadalena_U	3	0	3	0
T_Maravilla_U	3	0	3	0
T_NAYO_U1_U2	3	0	3	0
T_PLMRA_U1_U2	4	0	4	0
T_TGU2_U4_U6	3	0	3	0
T_TGUA_U1_U6	3	0	3	0
T2_EESP_EES	1	0	1	0
T4_COTO_COT	3	0	3	0
T_BARR_BAR	-2	0	-2	0
T_EL_SALTO	4	0	4	0
T_TR_ARPRTO	1	0	1	0
T_PERG_PER_2	1	0	1	0

The system have 96 two winding transformer and the table show the transformers with TAP´s are different of zero.

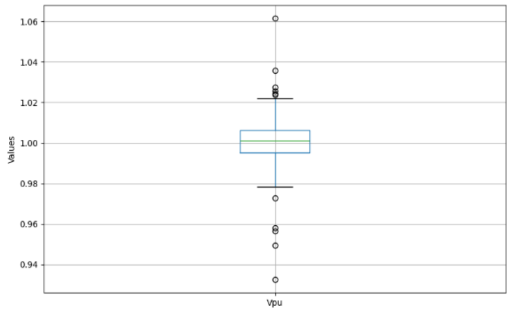
The per unit voltages (Vpu) all buses are describe in the following table, the Min and Max value are 0.93 and 1.06 that occurs in two buses of low voltages:

***Table 4.** Statistical summary in Vpu*

Statistical	Vpu
Count	187
Mean	1.000087
Std	0.012898
Min	0.932534
25%	0.995137
50%	1.001049
75%	1.006438
Max	1.061627

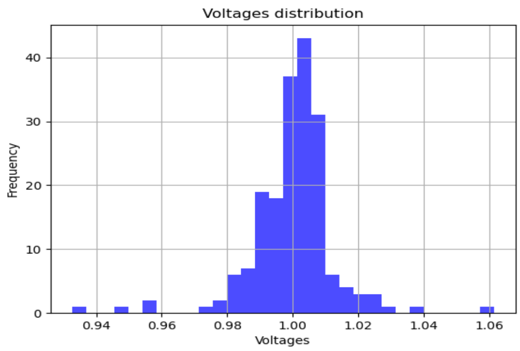
The whisker box is present per unit voltages of all buses, the majority of data are around 1 per unit. Theses voltages are very import for stability voltage.

***Fig. 4.** Per Unit Voltage*



The bus voltages we can observe the majority are close 1 per unit

***Fig. 5.** Per Unit Voltage*



Finally, the objective is 8.75 MW and the location optimal TAP's are previous. Therefore, the difference is

0.11 MW of reduction in the system.

6. Conclusions

The proposed methodology is very important because it helps to convexify the power flows that are non-linear and hard to solve, for this we used conic approximation of second degree. Therefore, the problem is linear integer for the integer variables of the transformer TAP's. These convex equations help to find the global optimum and uniqueness of the solutions to operate in real time.

For the validation of the model we used the 14-bar ieee test feeder that is meshed with two two-winding transformers and a three-winding autotransformer, the results of the taps location programmed in Gams and disgsilent are the same and the voltages are within the permissible operating ranges.

Finally, a simulation was performed in GAMS of the electrical system of the city of Quito, located in Ecuador, the normal flow with the tap located in position 0, the losses are 8.86 MW and using the proposed methodology is 8.75 MW reducing by 0.11 MW. The voltages are around 1 in per unit and meets the constraint that helps to maintain voltage stability, while the optimizer meets the optimal TAP's location.

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