Validation of Static Voltage Stability Estimation Studies Based on P–V Curves Using ETAP

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DOI: 10.29322/IJSRP.16.03.2026.p17111
https://dx.doi.org/10.29322/IJSRP.16.03.2026.p17111

Paper Received Date: 17th February 2026
Paper Acceptance Date: 15th March 2026
Paper Publication Date: 20th March 2026

Abstract- This article presents the validation of the results of the estimation of static voltage stability in electrical power systems, based on the analysis of P-V curves, using ETAP software. Voltage stability is estimated using these curves, which are obtained through multiple power flow simulations that allow stability parameters such as the Maximum Load Point (MLP), voltage collapse point, and static stability limit to be estimated. Subsequently, a static voltage stability study is performed using ETAP software to validate the P-V curves, as well as the previously estimated stability parameters. Several case studies with the 5 and 9 node power system are carried out to estimate voltage stability and validate the results using ETAP. The case study results show that the curves and parameters estimated using multiple power flow analyses match the results obtained using ETAP. Thus, the validation presented allows us to infer that it is possible to perform a correct and reliable assessment of the static voltage stability of power systems using estimated curves and parameters, which is of great importance when a commercial software license is not available. It is important to mention that static voltage stability estimation studies, such as the one presented in this paper, are much easier to perform and the results are obtained in less time than when using continuous power flow analysis or other similar tools.

Index Terms- Static voltage stability, P-V curves, power systems, ETAP

I. Introduction

In recent years, power grids around the world have undergone significant changes due to the integration of new transmission technologies, non-linear loads, renewable energy sources, and increased demand. These changes have led to greater complexity in power grids, causing systems to operate close to their thermal and static stability limits. Clearly, these conditions have posed security risks associated with voltage stability, thus it is important to prioritize dynamic and static analysis to ensure the safe and reliable operation of currently operating electrical networks [1]. Static voltage stability refers to the system ability to maintain the appropriate voltage level under steady-state operating conditions and in the face of gradual variations in load or generation [2]. Voltage instability can cause a significant decrease in the nodal voltage profile and trigger cascading events, leading to partial or total voltage collapses in the grid. These voltage collapses are commonly known as blackouts and have serious economic and social impacts [3].

When a substation experiences a load demand greater than its supply capacity, then voltage stability can be characterized as a local phenomenon. On the other hand, stability voltage is considered global when several electrical substations in the system experience voltage instability problems [4]. Voltage stability can also be classified in terms of simulation time into static and dynamic stability. Among the most commonly used tools for performing stability analysis are V-Q sensitivity analysis [5], P-V/Q-V curves [6], and continuation power flow analysis [7], which allow the behavior of the system to be evaluated under progressive load increases. The P-V curves used here are obtained by plotting the relationships between voltage magnitude and active power at the load nodes of the power system. These curves, by plotting the magnitude of the voltage as a function of the incremental variation in active power demand at each substation in the power system, allow various parameters to be calculated, such as the maximum load point, the voltage collapse point, the voltage stability margin, and the static voltage stability limit [8, 9, 10]. The presence of static voltage instability in the power system mainly results in a decrease in the nodal voltage profile, which can trigger the operation of low-voltage protection relays in several substations of the system, causing a widespread blackout in the power grid due to the simultaneous tripping of loads.

Static voltage stability analysis can be performed using the tools mentioned above. However, if this analysis is based on P-V curves, an estimate of voltage stability can be made, which can be carried out by performing multiple conventional power flow (PF) [11] or optimal power flow (OPF) [12] analyses. It is well known that conventional steady-state analyses based on FP and FPO have convergence limitations near the voltage collapse point, and therefore do not allow this point to be calculated accurately [2]. However, as mentioned, these tools can be used to obtain P-V/Q-V curves and perform a reliable estimation study of the static voltage stability of the power system. In addition, estimation studies using power flow analysis require less implementation and computation time, reducing the time needed to obtain results.

On the other hand, static voltage stability studies can be carried out using specialized commercial software packages such as ETAP [13], DIgSILENT Power Factory [14], PSS®E [15], among others. These packages have a module specifically dedicated to static voltage stability analysis using P-V/Q-V curves. Some studies have reported the use of these packages to carry out static voltage stability studies. For example, in [16], ETAP was used to perform a voltage stability study for combined cycle power plants, while in [17], the impact of synchronous condensers on voltage stability was evaluated using DigSILENT Power Factory.

solution is less complex than in the case of dynamic analysis and can be obtained in less time and with less computational effort. The basic concept of static voltage stability analysis can be understood by considering the radial system shown in Fig. 1, which consists of a generator supplying power $P_{gi}+jQ_{gi}$, a transmission line with series reactance jX, and a load demanding power P_l+jQ_l at voltage V_j.

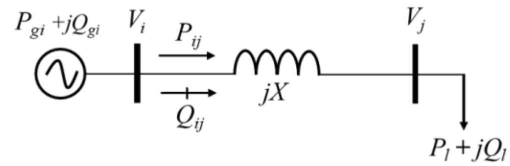

Fig. 1. Radial system for static tension stability analysis.

The power flow through the transmission line connected between nodes *i-j* is expressed by Equations (1) and (2) as follows,

$$P_{ij} = \frac{|V_i||V_j|}{|X|}\sin\delta_{ij} \tag{1}$$

$$Q_{ij} = \frac{|V_i|^2}{|X|} - \frac{|V_i||V_j|}{|X|} \tag{2}$$

Based on the above equations, a power balance is performed at node j to obtain the following equation:

$$|V_j| = \left[\frac{-2Q_L|X| + |V_i|^2 \pm \sqrt{A^2-4B}}{2}\right]^{1/2} \tag{3}$$

Where terms A and B are given as follows, In this context, this study validates the results of static voltage stability estimation studies based on P-V curves by comparing them with the results obtained using ETAP commercial software. To do this, a voltage stability estimation study is first carried out, obtaining the P-V curves through multiple power flow simulations and estimating critical voltage stability parameters. Subsequently, the results of the estimation study are compared with the results of a voltage stability study carried out in ETAP, which allows the results of the estimation to be validated. The structure of the article is as follows: Section II presents the fundamentals of static voltage stability and P-V curves, while the modeling of conventional power flow analysis and how to obtain P-V curves using PF are presented in detail in Section III. The case studies in which the validation of the voltage stability estimation results is carried out are presented in Section IV, while the conclusions of the work are presented in Section V.

II. STATIC STABILITY VOLTAGE OF POWER SYSTEMS

The dynamic analysis of voltage stability is modeled using differential equations that allow simulations to be performed in the time domain, while in the case of static analysis, algebraic equations are used to represent the system conditions, whose

$$A = 2Q\ \ X - V^{2} \qquad B = P^{2}\ \ X^{2} + Q^{2}\ \ X^{2} \qquad (4)$$

In Equation (3), the voltage magnitude of node j $|V_j|$, where the load is connected, depends on the active and reactive power demanded at this node. Thus, this equation can be used to obtain the P-V curves and analyse the static voltage stability of the radial system shown in Fig. 1.

The P-V curves shown in Figure 2 are obtained by plotting the active power demanded at a substation on the x-axis and the voltage magnitude of that substation on the y-axis. This is intended to illustrate the behaviour of the voltage magnitude in response to an increase in active power demand under steady- state operating conditions. The power-voltage curves have a “knee shape” in the area where the voltage decreases as the active power demand increases until it reaches the voltage collapse point. If the power demand increases beyond this point, the system experiences voltage instability and could collapse abruptly [4]. In general, P-V curves can be used to determine various parameters associated with stability, such as the voltage collapse point, from which it is possible to calculate the maximum load point, the voltage stability margin, and the static stability limit of a particular electrical substation.

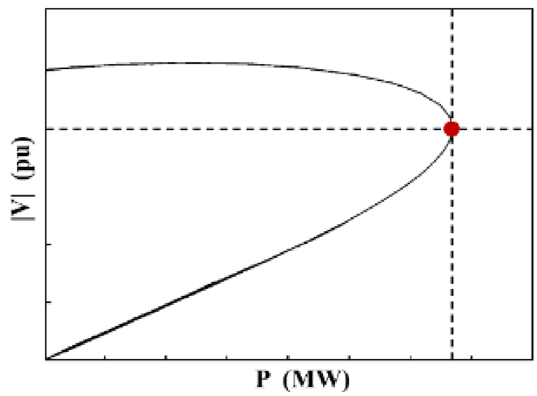

Fig. 2. P-V curve and voltage collapse point.

According to the figure above, on the P-V curve, the voltage collapse point corresponds to the intersection of the dotted horizontal line with the y-axis, while the MLP is the projection of

$_l|\quad|\quad|_i|\qquad _l|\quad|\qquad _l|\quad|$

ISSN 2250-3153

the variables to be determined are the voltage magnitudes and the nodal phase angle, such that the power balance defined by (5) and (6) is established. The phase angle and voltage magnitude are then used to calculate the active and reactive power flow, as well as the losses and power generated at the slack node and at the generation nodes.

The study to estimate static voltage stability proposed in this paper is carried out by executing various power flows,

the red point onto the x-axis. The static voltage limit of a node corresponds to the point whose coordinates are given by the MLP and voltage collapse.

III. Modeling Of Power Flow Analysis For Voltage Stability Analysis

As is well known, power flow analysis is one of the widely used tools for performing steady-state analysis of power systems, thus it can be used to carry out static stability estimation studies. The mathematical formulation of power flow analysis is described below, which is usually modelled using a system of nonlinear algebraic equations representing the active and reactive power balance at each node *i* of the power system, as shown in Fig. 3.

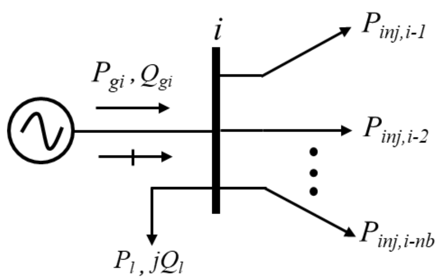

Fig. 3. Active and reactive power balance diagram at node *i*.

The algebraic equations representing the active and reactive power balance are given by (5) and (6) as follows [18],

$$P_{gi} - P_{li} - \sum_{j=1}^{nb} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) = 0 \qquad (5)$$

$$Q_{gi} - Q_{li} + \sum_{j=1}^{nb} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) = 0 \qquad (6)$$

In the above equations, the subscripts *g* and *l* denote the power generated and demanded at node *i*, while the active and reactive power injection at node *i* through element *j* is represented by the term containing the sum. As mentioned, the system of algebraic equations representing the power flow formulation is nonlinear; it can be solved using various numerical methods, such as the Gauss-Seidel method or the Newton-Raphson method and their modifications. In all methods,

considering gradual load increases given by a factor *k*, ranging from an initial value until reaching the Maximum Load Point. The gradual increases in active power demand are given by (7) [8], whose equation is integrated into (5) to perform the power flow analysis for each load value. This makes it possible to obtain P-V curves and estimate parameters for evaluating the static voltage stability of a power system.

$$P_{li} = P_{li,0}(1+k) \qquad (7)$$

In the above equations, the term *k* is the load increase factor, which is considered here as an integer that varies as k=0, 1, 2, …, k_{max}. When $k=k_{max}$, the maximum load point is obtained at the node under study. On the other hand, $P_{li,0}$ represents the base active power at node *i*, where the load is increased until reaching the MLP to estimate the static voltage stability of the power system. It should be noted that for each load increment value, a power flow analysis is performed; i. e., if the factor *k* has *n* load increments, then *n* power flow analyses are performed. This is done to obtain the voltage magnitude values for each active power demand value and to plot the P-V curves. As mentioned, the multiple power flow analysis used in this work does not calculate the critical stability points exactly, so the P-V curves and parameters calculated in this work are part of an estimation that allows the static voltage stability analysis to be carried out approximately and, at the same time, correctly, as illustrated in the case studies in the following section.

IV. Case Studies

The case studies presented in this section were carried out with 5 and 9-node power systems, whose data are specified in references [19] and [20], respectively. In addition, data of these power systems are given in the Appendix Section. In both cases, various simulations of the power flow analysis presented in Section III are used to obtain the P-V curves. Once these curves are obtained, the stability parameters, such as the maximum load point, the voltage collapse point, and the voltage stability limit, were estimated. Next, the two power systems are implemented in ETAP software to obtain the P-V curves and calculate the aforementioned stability parameters. This was done to compare both the curves and the previously estimated results, thus enabling their validation. The ETAP version used to validate the voltage stability results was version 22.5.0C with a commercial license for 500 nodes.

A. 5-node power system

The 5-node power system consists of 2 generators, 7 transmission lines, and 3 loads, as shown in Fig. 4.

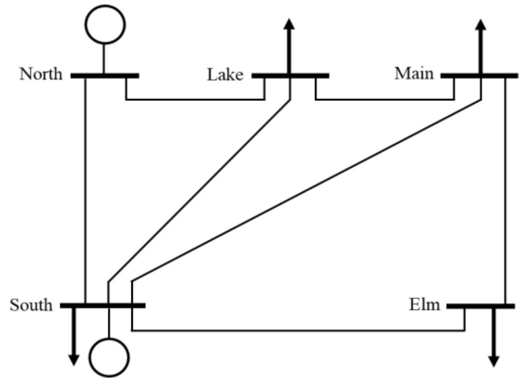

Fig. 4. 5-node power system.

Fig. 5 shows the P-V curves for nodes 3, 4, and 5, which are identified in the power system as load nodes. In this figure, the curves were obtained from estimated voltage magnitude results obtained through multiple power flow analyses. The computational algorithm used to carry out the case studies of the static voltage stability estimation was implemented in Matlab 2024a. It is important to note that the voltage stability curves were only plotted in the stable region of the load nodes.

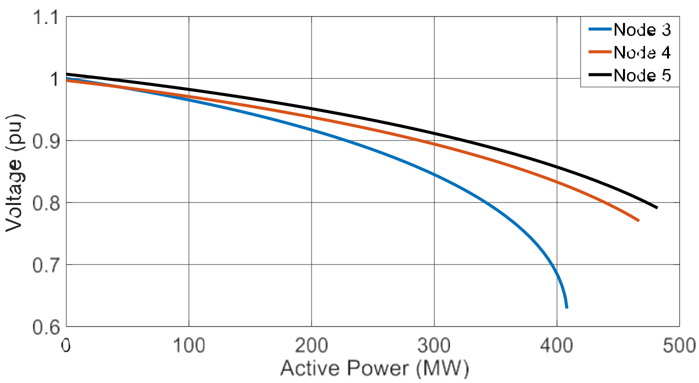

Fig. 5. P-V curves estimated using multiple power flows with the 5-node system.

Next, the 5-node system is modeled in ETAP software to obtain the P-V curves, as well as the parameters that allow the static voltage stability of this power system to be evaluated. It is important to mention that the curves presented in this paper were plotted in Matlab 2024a with data obtained using ETAP. This is because the graphs provided by this specialized software lack enough quality for presentation in the format of this paper, making them difficult to interpret and read. Therefore, the P-V curves of the 5-node power system obtained with ETAP software are shown in Fig. 6.

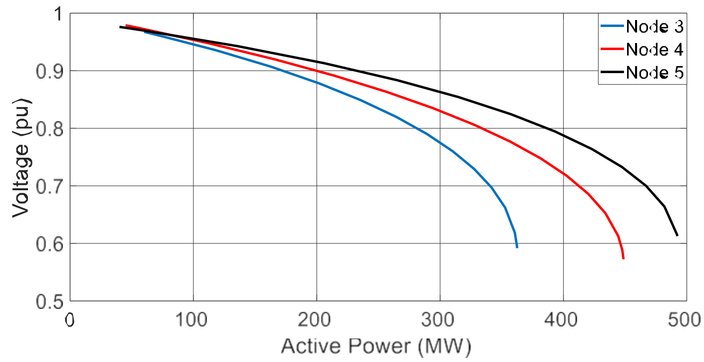

Fig. 6. P-V curves obtained using ETAP software with the 5-node system.

According to the P-V curves shown in the previous figures, it is possible to observe that they have very similar behaviors. In both figures, node 3 is the weakest in the power system, as it has a lower MLP and voltage stability margin. On the other hand, node 5 has a higher MLP and voltage stability margin. Thus, node 3 is where the greatest reactive compensation requirements and the lowest static voltage stability limit are found.

In order to validate the estimated voltage stability parameters calculated using power flow analysis, a comparison is made with those obtained using ETAP software. This comparison is presented in Table I. It is important to note that the values presented in this table were calculated from the P-V curves, using the graph in Fig. 2 as a reference.

Table I. Comparison of static voltage stability parameters for the 5-node power system.

	Parameters estimated using power flow analysis		Parameters calculated using ETAP software	
Node	**Maximum Load Point (MW)**	**Voltage Collapse Point (pu)**	**Maximum Load Poin (MW)**	**Voltage Collapse Point (pu)**
3	408	0.6291	362.29	0.5939
4	467	0.7705	448.55	0.5737
5	482	0.7912	492.07	0.6145

The static voltage stability limit considered in this paper is defined by the coordinates of the MLP and the voltage collapse point. Thus, for example, the estimated voltage stability limit of node 3 is given by (408, 0.6291). Clearly, the abscissa coordinate is the MLP, while the ordinate coordinate corresponds to the voltage collapse point. According to the figures and table presented, it can be observed that the behavior of the P-V curves and the estimated stability parameters values are very similar to those calculated by the ETAP software. Therefore, it can be inferred that the P-V curves estimated with power flow analysis behave similarly to those obtained using ETAP software. They can therefore be used reliably to evaluate the voltage stability of power systems, as they allow the weakest nodes and those with the highest voltage support capacity to be identified. They also help to determine an approximation of the static stability limit of the load nodes in the power system.

A. 9-node power system

Other case studies are conducted using a 9-node power system, which consists of 3 generators, 3 transformers, and 6 transmission lines. Fig. 7 illustrates a scheme of this power system.

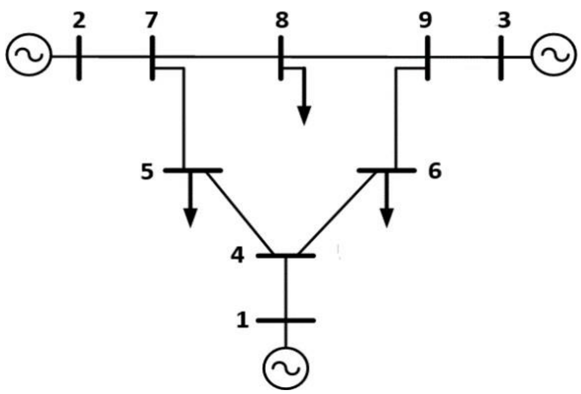

Fig. 7. 9-node power system scheme.

Similar to the previous system, multiple power flow analyses are performed to estimate the voltage magnitude as a function of active power in order to plot the P-V curves and calculate the MPL and the voltage collapse point at load nodes 5, 6, and 8. Likewise, the 9-node power system is modeled in ETAP software to compare and validate the estimated voltage stability results. Figures 8 and 9 show the P-V curves obtained through power flow analysis and with ETAP, respectively.

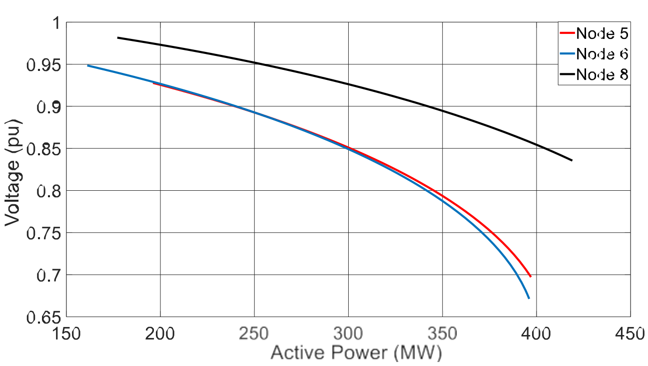

Fig. 8. P-V curves estimated using multiple power flows with the 9-node system.

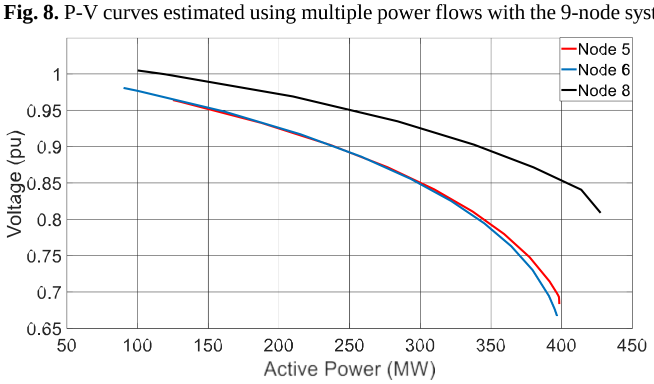

Fig. 9. P-V curves obtained using ETAP software with the 9-node system.

In this power system, based on the power-voltage curves in the previous figures, the stability parameters are also calculated, which are shown in Table II.

Table II. Comparison of static voltage stability parameters for the 9-node power system.

	Parameters estimated using power flow analysis		Parameters calculated using ETAP software	
Node	**Maximum Load Point (MW)**	**Voltage Collapse Point (pu)**	**Maximum Load Poin (MW)**	**Voltage Collapse Point (pu)**
5	397	0.6971	397.1	0.6962
6	396	0.6712	396.5	0.6674
8	419	0.8356	427.4	0.809

As can be seen in the figures above and in Table II, both the P-V curves and the estimated stability parameters are very similar to those obtained using ETAP software. Even in this power system, the estimated voltage stability limit is better than in the case of the 5-node system. This is probably due to the topology of the 9-node power system, since each system is unique and, in some cases, the estimated results can be better assimilated to some power systems than in other cases. However, the estimated results always maintain the same behavior as the ETAP software results, confirming the reliability of performing voltage stability studies based on estimated results using power flow analysis.

V. Conclusions

A validation of the results of static voltage stability estimation studies of power systems, based on P-V curves, using ETAP software has been presented. The P-V curves were obtained through multiple power flow simulations to estimate voltage stability parameters, such as the MLP, the voltage collapse point, and the static stability limit. The case studies showed that, despite differences between the estimated results and those calculated by ETAP, these variations do not affect the reliability of the estimated results, since they allow for the correct identification of weak nodes where there is less stability margin and a greater probability of instability voltage in the face of progressive load increases. Furthermore, depending on the power system, the case studies showed that good approximations of the parameters and voltage stability limits are obtained. It is worth noting that voltage stability studies based on estimated results are easier to implement and require less simulation time, allowing results to be obtained more quickly and easily compared to other tools, such as continuation power flow. Finally, it is important to mention that static voltage stability estimation studies of power systems, based on P-V curves, represent a viable alternative when specialized commercial software licenses are not available or when a preliminary assessment of the static voltage stability of power systems is required.

Appendix

The data of the 5- and 9-node power systems are presented below in the following tables.

Table III. Transmission line data of the 5-node system.

Node		R	X	G_C	B_C
Send	**Receive**	**(pu)**	**(pu)**	**(pu)**	**(pu)**
North	Lake	0.080	0.240	0.000	0.050
North	South	0.020	0.060	0.000	0.060
North	Lake	0.080	0.240	0.000	0.050
South	Lake	0.060	0.180	0.000	0.040
South	Main	0.060	0.180	0.000	0.040
South	Elm	0.040	0.120	0.000	0.030
Lake	Main	0.010	0.030	0.000	0.020
Main	Elm	0.080	0.240	0.000	0.050

Table IV. Generator data of the 5-node power system.

Node	Límits P_{gi} (MW)		Límits Q_{gi} (MVAR)		Cost curve coefficients		
	Min	**Max**	**Min**	**Max**	***a***	***b***	***c***
North	10	200	-500	500	0.006	0.034	0.004
South	10	200	-300	300	0.006	0.034	0.004

Note: *a*: \$/hr, *b*: \$/hrMW, *c*: \$/hrMW^2

TABLE V. Transmission line data of the 9-node power system.

Node		R	X	G_C	B_C
Send	**Receive**	**(pu)**	**(pu)**	**(pu)**	**(pu)**
4	5	0.0100	0.0850	0.000	0.1760
5	7	0.0320	0.1610	0.000	0.3060
7	8	0.0085	0.0720	0.000	0.1490
8	9	0.0119	0.1008	0.000	0.2090
9	6	0.0390	0.1700	0.000	0.3580
6	4	0.0170	0.0920	0.000	0.1580

TABLE VI. Generator data of the 9-node power system.

Node	Limits P_{gi} (MW)		Limits Q_{gi} (MVAR)		Cost curve coefficients		
	Min	**Max**	**Min**	**Max**	***a***	***b***	***c***
1	0	1000	-1000	1000	0.014	0.020	0.0060
2	0	200	-150	150	0.012	0.015	0.0075
3	0	200	-150	150	0.008	0.018	0.0070

Note: *a*: \$/hr, *b*: \$/hrMW, *c*: \$/hrMW^2

ACKNOWLEDGMENT

The authors gratefully acknowledge the funding provided by TecNM through the 2025 Call for Proposals "Support for the Strengthening of Academic Groups" belonging to the Budgetary Program "Program for the Professional Development of Professors PRODEP 2025", whose official letter M00/3089/2025 authorizes the release of funds for the development of the research project "Static Voltage Stability Analysis of Electrical Power Systems Considering the Integration of FACTS Devices"

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