Modeling and Performance Evaluation of an Electromagnetic Voltage Regulator via Series Compensation

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Abstract— **Although there currently exists a wide range of voltage regulators that are commercially available, the search for devices with a simpler physical design remains the focus of research studies. Following this line, an electromagnetic voltage regulator (EVR) arrangement has been proposed. The EVR is constituted of an autotransformer that supplies, via discrete taps, a series transformer that injects voltage for regulating the feeder voltage. Even though its operating principle is shown as being similar to that of other devices on the market, the physical arrangement and operating strategy of EVR show novelties which result in properties such as: economic attractiveness, constructive simplicity, and operational reliability. Moreover, when installing voltage regulators, efficacy studies must be carried out to optimize equipment design. In this context, this paper aims at evaluating the factors that influence the effectiveness of the EVR in restoring voltage variations according to the determinations imposed by regulatory agencies. The ultimate goal of this study is to determine the voltage deviation range that the EVR is able to restore. To achieve this goal, a mathematical modeling of the EVR is given and study cases are computationally carried out to investigate its performance when connected to a typical distribution feeder.**

Index Terms—**Computational Modelling, Distribution System, Electromagnetic Voltage Regulator, Performance Evaluation, Power Quality, Voltage Regulation.**

I. INTRODUCTION

AMONG the electrical power supply requirements imposed on power utilities, power quality indices are included, such as long-duration and short-duration voltage variations, harmonic distortions, unbalances, etc. In this scenario, the issues related to the voltage magnitude variations at power frequency are particularly highlighted, since distinguished normative documents establish limits for these phenomena in terms of long and short duration [1].

In Brazil, the definitions of voltage variation severity and duration are set by the Brazilian Electricity Regulatory Agency (ANEEL) in the technical standard titled Electricity Distribution Procedures in the National Electric System (PRODIST) - Module 8 [2]. This document classifies long-duration voltage variations as changes in the RMS value of the voltage over a period longer than 3 minutes. On the other hand, short-duration phenomena include those voltage variations manifested for periods shorter than the 3-minute limit. Moreover, the directive also establishes the magnitude limits for long and short duration voltage variation events.

When the voltage magnitude infringes the established limits, regulation or compensation processes are carried out in order to regulate the voltages to the acceptable levels defined by legislation. A wide range of equipment is currently employed to perform this task. In general, it is recognized that compensation devices are based on two basic strategies. The first comprises of voltage compensation by indirect methods, such as voltage control via static or dynamic devices associated with the control of reactive power flow. The second performs its function by acting directly on the voltage magnitudes using devices that change the voltage values via tap changers or direct injections of compensating voltage [3].

In the context of devices based on the control of reactive power, the simplest devices are capacitor and reactor banks – fixed or automatic [4]. Another possibility, widely used in the past in large power systems, is the synchronous compensator [5]. Further still, with the evolution of electronic switching technologies, commercial products that make use of the well-known FACTS technology have arisen [6]. This group includes the Static Var Compensators (SVCs) and Synchronous Static Compensators (STATCOMs).

Regarding compensation technology which acts directly on voltage magnitudes, traditional transformers with on-load tap changer (OLTC) and no-load tap changer (NLTC) [7] stand out, as well as other electromagnetic regulators based on tap changes to adjust the electrical quantities, such as the Step Voltage Regulator (SVR) [8]. Additionally, other devices, based on electronic switching, are available on the market. This is, for example, the case of the Dynamic Voltage Regulator (DVR) [9].

In light of the above, one recognizes, therefore, that there is a diversity of devices available on the market with operating properties capable of regulating the voltage at the load in

accordance with the required standards. However, the most widely used strategy to mitigate long-duration voltage variations, in distribution systems, is the direct compensation of the voltage magnitude [10].

Furthermore, in terms of the voltage regulators based on the direct compensation of the voltage magnitudes mentioned previously, there exists in this same category a device proposed in [11], which is called the electromagnetic voltage regulator (EVR). This device consists of a shunt autotransformer with taps supplying a transformer connected in series with the electrical feeder focused on the regulation process. The series transformer is responsible for the injection of a controlled reinforcement voltage, being that additive or subtractive, which aims at compensating the voltage at the load terminals. The fundaments that govern this proposal are found in [12], which shows that, via discrete switching, different taps of the autotransformer can be used to make the reinforcement voltage compatible with the required compensation level. The possibility of disconnecting the shunt autotransformer, as well as the switches, provides greater operational reliability for the network to which the EVR is connected. That is, in the event of a failure or maintenance of the regulator, despite the loss of the regulation process, the power flow between the source and the load is not interrupted.

In line with the aforementioned topological proposition, more recent works, such as [10] and [13], covering similar physical structures and commercial products have shown the feasibility of the arrangement focused upon in this paper. In fact, with a topology similar to the EVR, [14] describes a new conception for a voltage compensator, which was installed on a rural medium voltage feeder in Germany with high presence of distributed generation. The commercial equipment was called the line voltage regulator (LVR) and the results of its performance indicated great improvements in the voltage profiles of the rural medium voltage feeder. In addition to the operational effectiveness, the work highlights that the LVR presented a cost-benefit ratio higher than other options for voltage compensation, which significantly increased the network distributed generation capacity. Within the same constructive and operational strategy, [15] showed that the solution proved to be efficient for different voltage levels.

Even though the efficacy of the EVR injection has been verified for a constant load consumption [11] [12], its effectiveness for a load with dynamic behavior must be further investigated. In fact, variables such as the long-duration voltage variation magnitudes, the feeder and load parameters, and the available taps of the EVR are features that will strongly affect the performance of the device.

In this context, this paper aims at evaluating the relationship among these influencing factors since they define the range of voltage variations that the EVR can restore to the adequate voltage level set in the standards.

For a better understanding, initially, the physical arrangement and operating principle of EVR are presented, as well as the development of its mathematical modeling in the frequency domain. In the following, a detailed performance evaluation study and computational case studies are carried out to achieve the goal proposed in this paper.

II. ELECTROMAGNETIC VOLTAGE REGULATOR: PHYSICAL ARRANGEMENT AND MATHEMATICAL MODELING

Before deriving the mathematical model of the EVR, its physical arrangement is shown in the schematic diagram given in Fig. 1. It can be noted that the device enables the control of the load voltage (Bus 2) by injecting a series compensation voltage (additive or subtractive reinforcement), which, when summed to the supply voltage, leads to a controlled voltage at the load terminals.

In Fig. 1, the regulator is operating to restore the load voltage (Bus 2) when an undervoltage occurs on Bus 1. Once this phenomenon happens, the control on the regulator detects it and selects the tap of the autotransformer that offers the most adequate level of compensating voltage for injection into the system. This compensation voltage when summed to the supply voltage restores the voltage at Bus 2 to its required value or close to it. Subtractive voltages are also feasible for injection by the series transformer, in the case of overvoltages. This can be carried out by changing the contacts using the SWpp and SWpn switches.
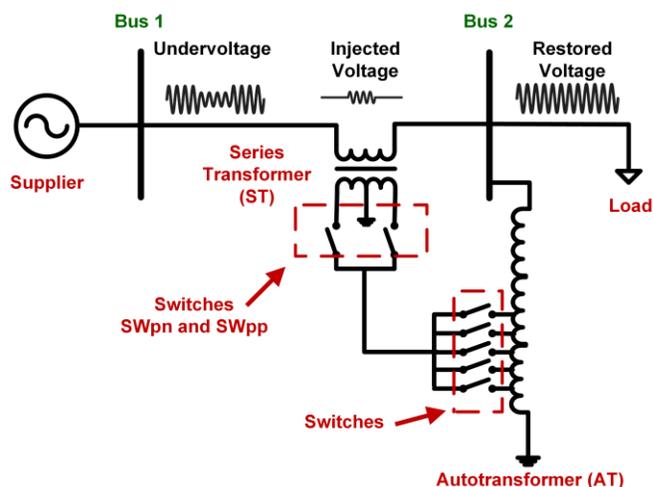

Fig. 1. Schematic diagram of the Electromagnetic Voltage Regulator. Adapted from [11].

The equivalent electrical circuit of the EVR and overall system arrangement, related to a specific steady state operational condition, is given in Fig. 2. Noteworthy here is that the equivalent circuit shown is applicable to a given selected tap when operating to restore undervoltages.

The corresponding equation to establish the relationship among the system (EVR, load, and feeder) parameters and the load voltage is given by (1). Noted also is that the magnetizing branches of the transformers are disregarded. The variables in (1) are identified in (2) to (5).
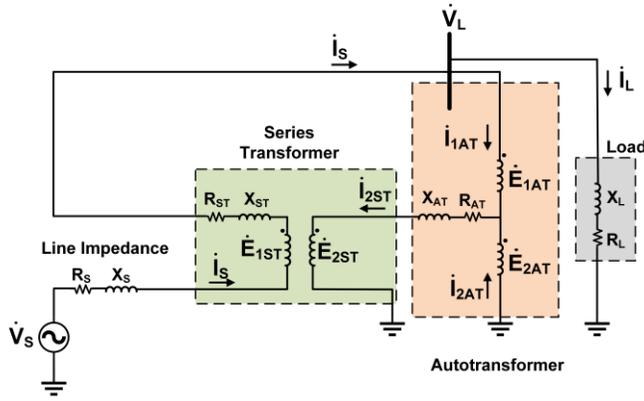
Fig. 2. Equivalent electrical circuit of the EVR, feeder and load.

$$\dot{V}_L = \frac{\dot{V}_S}{1 - \dfrac{\alpha_{ST}}{\alpha_{AT}} + \dot{K}_1 + \dot{K}_2} \tag{1}$$

$$\dot{K}_1 = \left(\frac{\alpha_{ST}^2 . \alpha_{AT}}{\alpha_{AT} - \alpha_{ST}}\right) * \frac{\dot{Z}_{AT}}{\dot{Z}_L} \tag{2}$$

$$\dot{K}_2 = \left(\frac{\alpha_{AT}}{\alpha_{AT} - \alpha_{ST}}\right) * \frac{\left(\dot{Z}_{ST} + \dot{Z}_S\right)}{\dot{Z}_L} \tag{3}$$

$$\alpha_{AT} = \frac{E_{1AT} + E_{2AT}}{E_{2AT}} \tag{4}$$

$$\alpha_{ST} = \frac{E_{1ST}}{E_{2ST}} \tag{5}$$

where:

- $\dot{V}_S$ is the supply voltage.
- $\dot{V}_L$ is the voltage at the load terminals.
- α_{AT} is the transformation ratio of the autotransformer.
- α_{ST} is the transformation ratio of the series transformer.
- $\dot{Z}_S$ is the supply network short-circuit impedance.
- $\dot{Z}_{ST}$ is the total impedance of the series transformer referred to the primary side.
- $\dot{Z}_{AT}$ is the total impedance of the autotransformer referred to the secondary side.
- $\dot{E}_{1ST}$ and $\dot{E}_{2ST}$ are the voltages on the primary and secondary sides of the series transformer, respectively.
- $\dot{E}_{1AT}$ and $\dot{E}_{2AT}$ are the voltages on the primary and secondary sides of the autotransformer, respectively.

III. A CASE STUDY OF THE EVR PERFORMANCE

In order to carry out the performance investigation of the overall system arrangement and the EVR effectiveness during the occurrence of voltages deviations from the standard values, a typical electrical system has been utilized. It consists of a radial feeder, whose parameters are found in Table I. It is noteworthy that, without the action of the regulator, the connection of the rated load to the feeder leads to a voltage drop of about 3.5% at the series impedance, assuming the supply voltage is 1 pu.

TABLE I
FEEDER AND LOAD CHARACTERISTICS

Parameter	Value
Rated Voltage	13.8 kV
Network Short Circuit Power	200 MVA
R/X ratio	0.5
Load Power Factor	0.94 (lag)
Rated Load Power	10 MVA

As for the EVR, the compensator is connected to the feeder, in accordance with the electrical circuit of Fig. 2. Its regulation range (Reg. Range) goes up to ± 20% in steps of 2.5%. The autotransformer has 8 taps, therefore, the EVR, via its tap 8, is capable of providing a maximum line voltage of:

$$V_{1ST} = \text{Re}g. \ Range(pu) * V_{RATED}$$
$$V_{1ST} = 0.2 * 13.8kV = 2.76kV \tag{6}$$

In order to reduce the current level of the switches of the taps, the transformation ratio of the series transformer was chosen as $\alpha_{TS} = 0.5$. One is reminded that under this condition, the current on the primary side of the series transformer will be 50% of the feeder (load) current. Therefore, due to this transformation ratio of the series transformer, the voltage on the secondary side of the autotransformer must be twice the voltage value intended for injection. Taking tap 8 as an example, to achieve a compensating voltage of 20%, it is necessary that the voltage on the secondary side of the autotransformer be 40% of the feeder rated voltage. Similar reasoning applies to the other taps.

Regarding the rated power of the transformers, both autotransformer and series transformer have the same rated power, as determined by (7).

$$S_{ST} = S_{AT} = \left(\frac{\text{Re}g \ Range(pu)}{1 - \text{Re}g \ Range(pu)}\right) * S_{LOAD} \tag{7}$$
$$S_{ST} = S_{AT} = 2.5MVA$$

where:

- S_{ST} is the rated power of the series transformer.
- S_{AT} is the rated power of the autotransformer.
- S_{LOAD} is the rated load power.

Table II provides the characteristics of the two electromagnetic units that make up the EVR. The impedances and resistances are in line with typical designs.

TABLE II
SERIES TRANSFORMER AND AUTOTRANSFORMER CHARACTERISTICS

Data	Power (MVA)	Primary/Secondary Winding Voltages	Zcc (%)	Rcc (%)
Series Transformer	2.5	2.76/5.52 kV	5	1
Autotransformer	2.5	13.8 kV/Taps	5	1
Autotransformer taps – Secondary Winding Voltage		5.52 kV (Tap 8) – 4.83 kV (Tap 7) 4.14 kV (Tap 6) – 3.45 kV (Tap 5) 2.76 kV (Tap 4) – 2.07 kV (Tap 3) 1.38 kV (Tap 2) – 0.69 kV (Tap 1)		

Once the feeder, the load, and the design characteristics of the regulator are defined, the premises for the studies are listed as follow:

- The studies performed are associated with phenomena classified as long-duration voltage variations.
- According to the criteria defined in [2], the voltage values between 0.93 pu and 1.05 pu are considered as adequate. This voltage range is delimited by the green region of Fig. 3.
- When the limits of this range are violated, the action of the voltage regulator is represented, for each tap of the autotransformer, by lines that are changed according to the tap used.

Fig. 3 shows, initially, that the supply network suffers a 0.15 pu voltage drop. Then, with the load disconnected, the load voltage reaches the value of 0.85 pu. Once such a voltage variation is detected by the equipment control, the EVR starts to operate using tap 4 of the autotransformer – the corresponding reinforcement voltage is 2.76 kV, therefore, $\alpha_{AT-TAP4}$ is equal to 5, as shown in (8). Thus, still in the condition of the disconnected load, (9) shows that the load voltage increases to 0.94 pu. This value is obtained by (1) when K_1 and K_2 are equal to zero, as such; it corresponds to the maximum compensation achieved by tap 4.

$$\alpha_{AT-TAP4} = \frac{13.8kV}{2.76kV} = 5 \quad (8)$$

$$\dot{V}_L = \frac{\dot{V}_S}{1 - \frac{\alpha_{ST}}{\alpha_{AT-TAP4}}} = \frac{0.85}{1 - \frac{0.5}{5}} = 0.94\,pu \quad (9)$$

where:

$\alpha_{AT-TAP4}$ is the transformation ratio of the autotransformer when tap 4 is selected.

Therefore, under the above-mentioned conditions, tap 4 was sufficient for restoring the voltage to the appropriate range. However, as the load is connected and its power increases the complex coefficients K_1 and K_2 change, and despite the injection of the voltage from tap 4 being maintained, as expected, the load voltage gradually decreases; the decay rate is defined by the feeder and series transformer impedances. Fig. 3 shows that, starting from a 3 MVA load, tap 4 is no longer sufficient to adjust the load voltage to the adequate range. Then, the control changes to tap 5, and a new line starts in Fig. 3, with a similar decay behavior, however, starting with an adequate voltage value. When the load becomes equal to 7.9 MVA, the situation repeats once more.
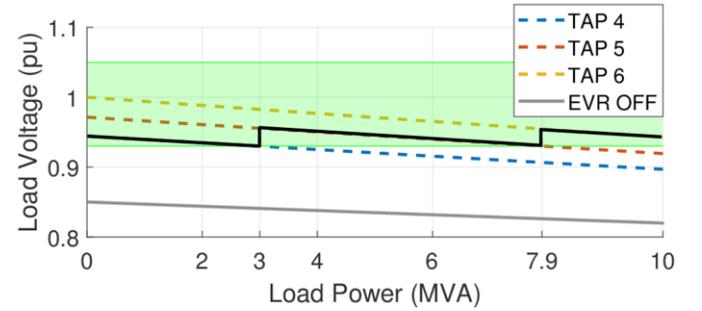

Fig. 3. Correlation between the load voltage and the load power for an undervoltage of 0.85 pu.

The results of the performance studies carried out so far reveal that the voltage compensation efficacy decreases with the increase of the load power, for each tap, as expected. Therefore, in order to maintain the load voltage within the adequate range, it becomes necessary to change the tap to compensate for the loss of regulation efficiency caused by the increase in the K_1 and K_2 coefficients, according to (1).

Moreover, the dynamics of the control and switching system will define the regulator response time for the voltage regulation.

From another evaluative aspect, performance studies are now carried out for a constant 10 MVA load under different undervoltages that occurred on the network. In doing so, the behavior of the set source-feeder-EVR-load is considered for various undervoltage magnitudes, and the effectiveness of the voltage regulation is evaluated for the 8 taps, as shown in Fig. 4.

Fig. 4 shows that under different undervoltages, as the taps of the autotransformer change from 1 to 8 (increasing the reinforcement voltage), the load voltage also rises as desired. The graph shows that each tap determines an undervoltage limit for which the EVR is able to ensure that the load voltage is within the adequate range. Consequently, the most critical undervoltage magnitude that the EVR is effective in restoring is set by tap 8. The figure indicates that for a 10 MVA load the regulator is capable of compensating, for the adequate range, undervoltage magnitudes up to 0.8 pu at the supply voltage.
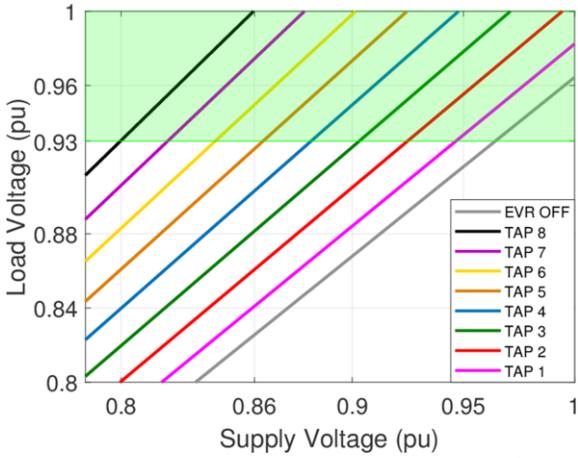
Fig. 4. Undervoltage magnitudes compensated by the EVR according to the autotransformer tap for a 10 MVA load.

IV. DYNAMIC RELATIONSHIP BETWEEN UNDERVOLTAGES PHENOMENA AND THE EVR EFFECTIVENESS

In addition to the studies related to the previously presented operational limits, this section aims at showing the dynamic performance of the EVR under specific operating conditions. Hence, the system used as a case study was implemented in the MATLAB Simulink, as shown in Fig. 5. The parameters of the system are the same as those shown in Tables I and II.

The two operational situations considered are the following:

- Case 01: Initially, the 13.8 kV voltage supply (1 pu) feeds the rated load (10 MVA). At t = 0.5 s, the supply voltage drops to 11.73 kV (0.85 pu). Then, the EVR is set to turn on at t = 1 s with tap 8 selected.
- Case 02: This situation is similar to the previous one, except for the fact that the voltage drop is more severe (10.35 kV or 0.75 pu).

A. Case 01 - Undervoltage of 0.85 pu

Fig. 6 presents the voltage profile at the load terminals. It is shown that, between t = 0 and 0.5 s, the load voltage has a value of 13.25 kV (0.96 pu). The 0.04 pu voltage drop is due to the feeder impedance. At t = 0.5 s, the load voltage reduces to 11.27 kV (0.82 pu), due to the voltage variation imposed on

the supplier. Next, at t = 1 s the regulator starts operating, with the autotransformer switched to tap 8. Under these conditions, the load voltage is restored to 13.69 kV (0.99 pu), thus showing the effectiveness of the regulator.
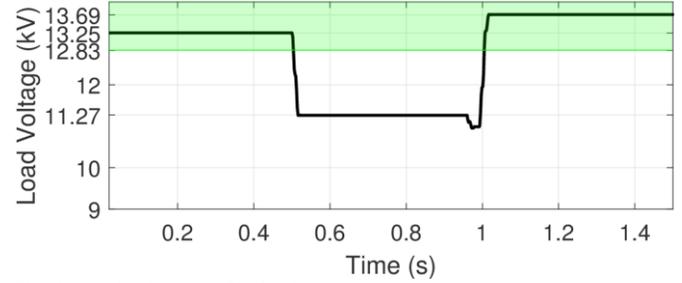

Fig. 6. Load voltage profile for Case 01.

B. Case 02 - Undervoltage of 0.75 pu

The results associated with a more drastic undervoltage are indicated in Fig. 7. As one notes, from 0 to 0.5 s the load voltage remains at 13.25 kV (0.96 pu) and, then, the load voltage is suddenly reduced to 9.94 kV (0.72 pu). After the regulator insertion, at t = 1 s, with the autotransformer switched to tap 8, the load voltage is increased to 12.08 kV (0.87 pu). Therefore, for this situation, the EVR does not have sufficient characteristics to restore the load voltage to the adequate range. In fact, the specified regulator is capable of restoring undervoltages up to 0.80 pu for a 10 MVA load. Despite the demonstrated limitation, the load voltage increased from 0.72 pu to 0.87 pu, which lessens the voltage variation at the load bus.
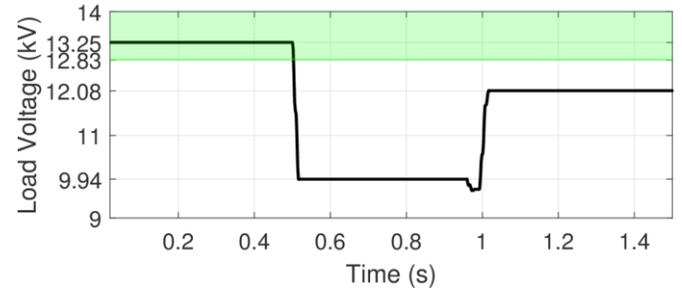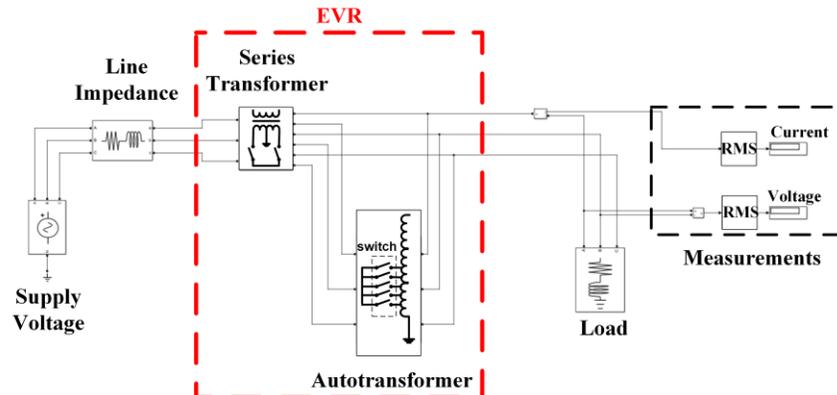

Fig. 7. Load voltage profile for Case 02.

Fig. 5. System implemented in the MATLAB Simulink.

The main electrical quantities associated with the operating conditions of the EVR, for the two cases analyzed, are summarized in Table III. Comparing those to the rated currents of the series transformer (105 A) and the autotransformer (523 A), the values obtained are within the rated characteristics of these electromagnetic components. The same applies to the voltage on the primary side of the series transformer.

TABLE III
CURRENTS AND VOLTAGES ASSOCIATED WITH THE STUDIED CASES

Electrical Quantity	Case 01	Case 02
I_L	415.1 A	366.2 A
I_S	518.9 A	457.8 A
I_{1AT}	103.8 A	91.6 A
V_{1ST}	2.61 kV	2.3 kV

Finally, Fig. 8 highlights the EVR performance for other load power values, previously fixed at 10 MVA. The figure shows the undervoltage magnitudes that the regulator is capable of restoring to the adequate range at the load bus. As expected, as the load power is reduced, the EVR can restore more severe undervoltage magnitudes.
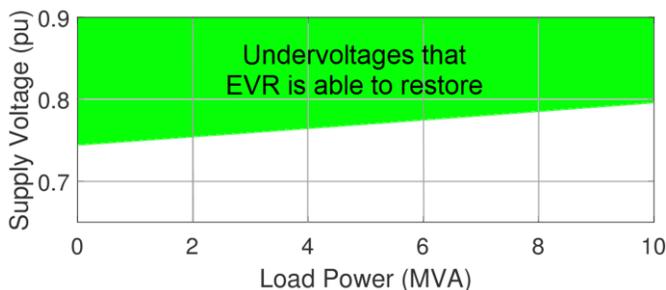

Fig. 8. Undervoltage magnitudes compensated by the EVR for the adequate range according to load power.

V. CONCLUSIONS

This paper presented an electromagnetic device for compensating voltage variations. The proposal acts directly on the load voltage by inserting a reinforcement – additive or subtractive – to restore the voltage magnitude to the standards established by legislation. The device has an attractive operating strategy given the use of components that offer constructive and operational simplicity, reliability, attractive costs, versatility of installation in uncontrolled environments, among other attributes. In order to contextualize the theme, general information concerning the physical arrangement and mathematical modeling of the regulation process was synthesized. As exposed in the introduction, the EVR was initially proposed by [11] and a similar device was materialized as a commercial product by [14] [15]. Once the device physical and mathematical model were presented, studies related to the effectiveness of the device when faced with typical influence quantities of electrical networks were carried out. The results clearly showed that the EVR, in the

terms designed and defined by its basic characteristics, also presents a strong dependence on the feeder and load parameters. Its efficacy may be full, partial or insufficient, depending on the variables involved in the voltage regulation process. In general, the results obtained are encouraging for the diffusion of the technology contemplated herein. Regarding the discrete response and the use of the EVR for restoring short-duration voltage variations, it can be implemented with fine-tunes based on the use, for example, of electronic techniques for controlling switches continuously, which is a subject for future works. Finally, it should be noted that, although the study presented has explored phenomena associated with undervoltages in the supply network, the regulator can also be used when overvoltages occur on the network.

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