



A Computational and Experimental Performance Analysis of an Electromagnetic Voltage Regulator Proposal throughout Controlled Series Voltage Injection

F. P. Santilio, T. V. da Silva, J. C. de Oliveira and J. A. F. Barbosa Jr.

Faculty of Electrical Engineering
Federal University of Uberlandia

Uberlândia, 38408-900 Minas Gerais (Brazil)

Phone/Fax number: +55 34 3239 4733, e-mail: fabricio.tee@gmail.com, tvsilva@gmail.com, jcoliveira@ufu.br and johnareis@gmail.com

Abstract. Power quality problems related to short or long time voltage variation have motivated the search for voltage compensator techniques capable to provide dynamic voltage regulation to accomplish voltage supply levels in accordance with electrical energy agencies acceptable levels. Although one could recognize that a variety of products already offered in the market are capable of attending general electrical power system requirements the available technology comprises quite simple devices till very sophisticated ones. Having in mind the combination of simplicity, competitive cost, low maintenance need and an attractive performance at recovering the voltage deviations, then an electromagnetic concept to restore the desirable voltage within the established voltage levels is here proposed. The control strategy to be used can provide properties that enable this new device at proving the time response in accordance with the needs for long term and short term voltage variations. Concerning the proposed compensator physical topology it consists in extracting the necessary electrical power throughout a shunt transformer and the injection via a series unit. Besides the arrangement, the paper goes further by establishing a computational time domain model and a laboratory experiment to highlight the overall structure effectiveness at compensating voltage changes.

Key words

Automatic voltage control, Power Quality, Power distribution, Electromagnetic Devices, ATPDraw.

1. Introduction

The matter of maintain voltage level within the standard values as given by the regulation agencies all over the world has emerged as one of the most important tasks to be fulfilled. To achieve such purposes different technologies have been traditionally utilized and commercially available in the market. One of the most well-known techniques is the classical compensation based on the injection or the consumption of variable reactive power, such as that provided by fixed or dynamic capacitor banks, reactors and synchronous compensator. Power electronic devices have also been developed to offer dynamic reactive arrangements having a similar physical behavior as the previous solutions. Another philosophy could be attributed to the direct injection of voltage reinforce has been largely

proposed. Within this later context arise the modern products such as the general UPFC and other type of products. These are, for instance, the well-known commercially equipment namely: DVR, Statcom, Sipcon, Power Conditioners, etc. These have emerged as means to restore voltage deviation to the admissible range with a very quick response time [3] [4] [5] [6].

Although the recognition of the effectiveness of the above solution, the search for new technologies has emerged the idea of using a power device conception based only on electromagnetic units that are to be switched in a discrete manner to obtain the necessary compensation voltage that will be injected in series with the main feeder. The proposed equipment can be comprised as having two main power electromagnetic units: The first one being the shunt unit – an autotransformer – to extract power flow from the grid, and a second one being a series unit – a transformer – destined to impose a voltage drop or a voltage rise achieving this way the level requirement imposed by the electrical agencies standards [7]-[9]. It worthwhile notice that the rated power for each of individual unit does not represent the total power feeding a given consumer but just a percentile of the total value supplied to the load. As a matter of fact, the power required and to be extract and injected by the compensator parts will be directly defined by the level of compensation to be offered. Within these principles, a device combining simplicity, low maintenance requirements, attractive initial costs, time response possibility to cope with short and long term voltage variations, amongst others properties, is here considered.

Therefore, the present paper focuses the description of the physical structure concerning the electromagnetic arrangement, a computational modeling in the ATPDraw time domain simulator and an experimental set up to provide means of investigating the overall complex at compensating sudden voltage occurrences at the mains. The results given in terms of a variety of operational conditions highlights the proposed compensator operation and effectiveness at restoring the consumer busbar voltage during supply system disturbances.

2. The Series Voltage Regulator Physical Structure

Fig. 1 illustrates the equipment topology focused in this paper. The hypothetical system is characterized by a single-line diagram which consists of a supplier, consumer and compensation voltage structure. The arrangement is showing the electromagnetic device, among other characteristics as: the shunt unit to extract power flow from the grid, a transformer to impose series voltage with the main feeder and the switching mechanism.

As far as the switching module concerns, this could be made of typical contactors or electronics switches, together with a logic control unit becoming an automatic structure to select the best tap compensation. The automatic structure time response to obtain voltage regulation is direct linked to the switch type, then, the restoration of voltage deviation could be adjust to the ones necessity. The authors emphasizes that the switching module used in this paper is composed by ideals switches in an open-loop control.

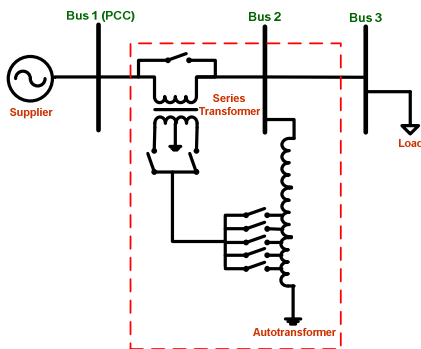


Fig. 1. Electromagnetic voltage compensator physical structure.

Fig. 2 enlightens, in a simple manner, the action of the voltage compensation device. It worth noticing that the series voltage injection is made by the best voltage tap amplitude from the autotransformer, allied by choosing its polarity, performing this way, the required voltage compensation.

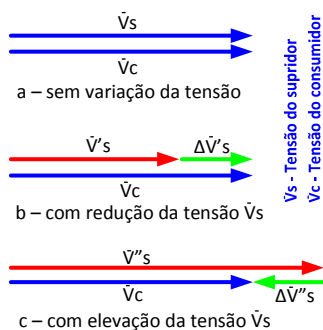


Fig. 2. Phasor diagram of the electromagnetic device performance.

3. Evaluation Study Strategy

The evaluation study, in accordance to the paper proposal, is divided in two strategies, being:

A. Computational performance and analysis

Using conventional ATPDraw simulator library facilities and by developing special routines throughout the MODELS platform to cope with the measurement device, the open-looped control unit and the specified switches, the final computational model is represented by Fig. 3. This figure, represent the work final result, shows the autotransformer, the series transformer, the switching module device and the open-loop control. It must be pointed out about the performance studies, in time domain, allowed by the chosen software, the analysis of dynamic, steady-state and transitory cases.

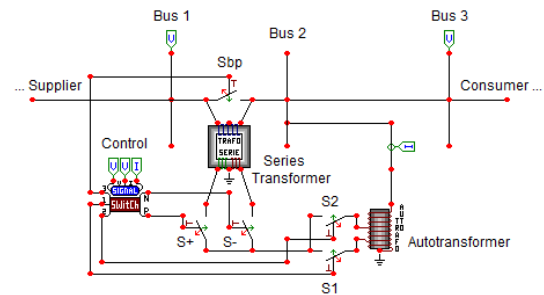


Fig. 3. The electromagnetic voltage regulator model in ATPDraw Platform.

Table I summarizes the main information about the electromagnetic components to form the voltage regulator device.

TABLE I. – Computational System Parameters

Dada	Power (VA)	Power Factor	Voltage (V)	Zcc%	Rcc%
Autotransformer	225	-	127/Tapes	12,5	10,0
Series Transformer	225	-	1:1	12,5	10,0
Load	528,8	1	127	-	-

To restore voltage deviation the autotransformer was designed with five taps: $\pm 5\%$, $\pm 10\%$, $\pm 15\%$, $\pm 20\%$ e $\pm 25\%$. The reason to choose these values was the voltages deviation performed at the main feeder to evaluate the electromagnetic device operational response.

B. Laboratory performance and analysis

Aiming at acquiring a laboratory physical structure capable of perform and simulate the response impose by the electromagnetic device, three usual pieces of equipment was combined to form de voltage regulator. The authors states that the arrangement used do not yet is a reduce scale prototype. Fig. 4 illustrates the laboratory equipment used to restore voltage deviations.

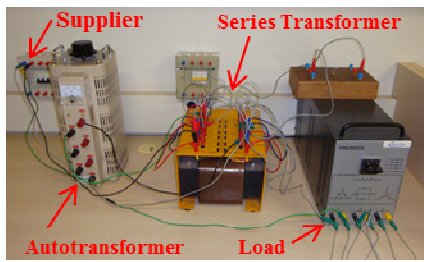


Fig. 4. Laboratory structure to perform the voltage regulation studies

Table II summarizes the main information about the conducted experiment.

TABLE II. – LABORATORY PHYSICAL ARRANGEMENT

Dada	Power (VA)	Power Factor	Voltage (V)
Autotransformer	1500	-	127/Tapes
Series Transformer	1500	-	1:1
Load	528,8	1	127

4. Case Studies Characteristics

For the computational and experimental analysis, among infinite types of situations, the authors choose to perform voltage deviations, over and above its nominal value. The set of simulations could be visualized through Fig. 5 and table III where a 48 seconds analysis, divided in 4 seconds intervals, totalizing 12 intervals, was conducted, each one linked to an operative condition. In this way, to example the simulation, from 0 to 24 seconds, that is, the first 6 intervals, it can be noticed a 5% slight voltage decrease in relation to the voltage nominal value. At 24 seconds, the voltage was restored to its nominal value and a 5% slight voltage increase was conducted till the end of the simulation.

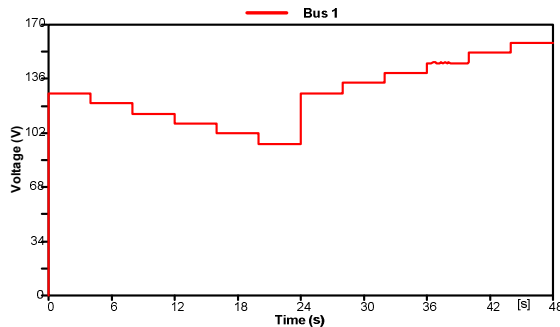


Fig 5. Busbar 1 voltage profile – Imposed voltage deviation and simulation intervals

TABLE III. – OPERATIVE CONDITIONS LINKED TO THE VOLTAGE AT BUSBAR 1

Interval	Time [s]	Voltage [V]	$\Delta V\%$
Interval 1	0 to 4	127,0	0
Interval 2	4 to 8	120,6	-5
Interval 3	8 to 12	114,3	-10
Interval 4	12 to 16	107,9	-15
Interval 5	16 to 20	101,6	-20
Interval 6	20 to 24	95,2	-25
Interval 7	24 to 28	127,0	0
Interval 8	28 to 32	133,3	+5
Interval 9	32 to 36	139,7	+10
Interval 10	36 to 40	146,0	+15
Interval 11	40 to 44	152,4	+20
Interval 12	44 to 48	158,7	+25

Once exposed the voltage deviations there will be the necessity of voltage correction at the load busbar. For the present paper, it implies at the already mention 5 chosen taps from the shunt unit – the autotransformer, as it can be seen in table IV.

TABLE IV. – AUTOTRANSFORMER TAPS – ADDITIVE AND SUBTRACTIVE

Tapes	1	2	3	4	5
Tensão (V)	7,5	14,0	19,9	26,9	33,9

5. Results and Discussions

After the voltage profile with no compensation has been given, by computationally and experimentally including the effect of the electromagnetic device, a new system performance has been obtained. The final busbar voltages are illustrated in Fig. 5 which shows results related to Bus 1 and 3. The Fig. 5a shows the result obtained computationally and Fig. 5b the results obtained experimentally.

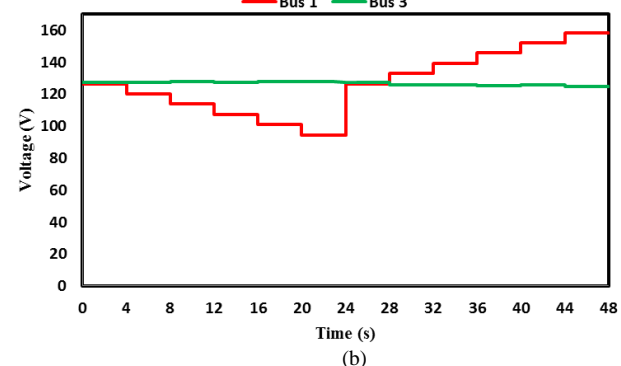
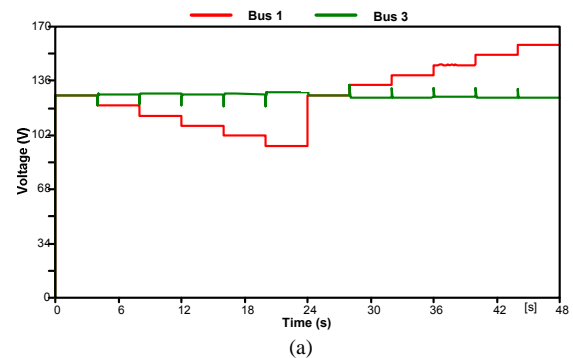


Fig. 5. Busbar 1 and 3 voltages: (a) Computationally (b) Experimentally

Table V presents the voltage RMS values found to Bus1 and Bus3 with the imposed supply disturbances. The deviations from the rated value are also included.

TABLE V. - BUS 1 AND 3 RMS VOLTAGES – EQUIPMENT CONNECTED

Time [s]	$\Delta V\%$	Computationally		Experimentally	
		Busbar 1 [V]	Busbar 3 [V]	Busbar 1 [V]	Busbar 3 [V]
0 to 4	0	127,0	127,0	126,5	126,5
4 to 8	-5	120,7	127,8	120,1	127,5
8 to 12	-10	114,3	127,9	113,7	127,7
12 to 16	-15	108,0	127,4	107,3	127,5
16 to 20	-20	101,6	128,1	100,9	127,7
20 to 24	-25	95,3	128,5	94,4	127,6
24 to 28	0	127,0	127,0	126,5	126,5
28 to 32	+5	133,4	125,7	132,9	125,8
32 to 36	+10	139,7	125,7	139,3	125,9
36 to 40	+15	146,0	126,0	145,7	125,4
40 to 44	+20	152,4	125,6	152,1	125,6
44 to 48	+25	158,7	125,2	158,4	125,0

In a complementary way, Fig. 6 presents the voltage and current behavior at secondary side of the shunt, which, in this paper, is considered the primary side of the series transformer. Fig. 6a is related to the results acquired in the computational simulation and Fig. 6b presents the same quantities tow referred to the laboratory experimental arrangement. The corresponding voltage and current values are given at Table VI.

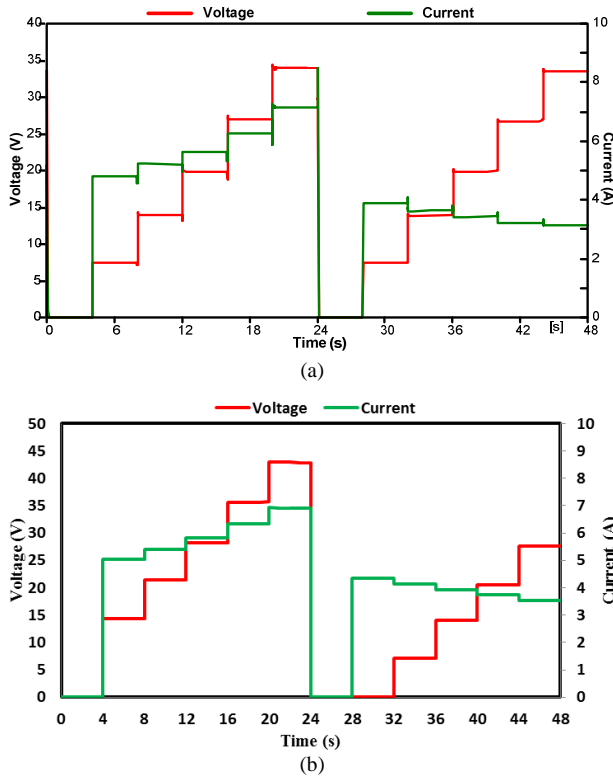


Fig. 6. Voltage and Current imposed by the shunt unit in the primary side of the series transformer: (a) Computationally (b) Experimentally

TABELA VI. – TENSÃO E CORRENTE IMPOSTA PELO AUTOTRANSFORMADOR NO SECUNDÁRIO DO TRANSFORMADOR SÉRIE

Time [s]	$\Delta V\%$	Computationally		Experimentally	
		Voltage [V]	Current [A]	Voltage [V]	Current [A]
0 to 4	0	0	0	0	0
4 to 8	-5	7,5	4,8	14,3	5,0
8 to 12	-10	14,0	5,2	21,4	5,4
12 to 16	-15	19,9	5,6	28,2	5,8
16 to 20	-20	26,9	6,2	35,6	6,3
20 to 24	-25	33,9	7,1	42,9	6,9
24 to 28	0	0	0	0	0
28 to 32	+5	7,4	3,9	0,1	4,3
32 to 36	+10	13,8	3,6	7,0	4,1
36 to 40	+15	19,8	3,4	14,1	3,9
40 to 44	+20	26,7	3,2	20,4	3,7
44 to 48	+25	33,4	3,1	27,5	3,5

Once analyzed the computational and experimental results, one could notice, after the first imposed voltage deviation, a significant distance between the each results. This inconsistency is due to the fact that there is a voltage drop at the series transformer secondary of 6.8Volts. As a result of this fact, there was the necessity to adjust the compensation value by changing the selection tap module for voltage correction. To point out an example, the first interval which occurs a 5% voltage decrease, is emphasized. So, to restore the voltage deviation at the load

busbar is was necessary to select the 10% voltage deviation tap to restore to its nominal value, that is, a 5% voltage drop from the series transformer secondary added to a 5% voltage decrease at the main feeder. In a complementary way, the contrary could be noticed in a voltage increase simulation study. For a 10% voltage rise at the main feeder, which is represented by time 32 to 36 seconds, the select tap to correct the voltage deviation was a 5% subtractive.

Aiming at providing a fully understand of the mechanism used to compensate the voltage deviation and the quantities values involved at this process, Fig. 7 presents the current flowing at different measuring points of the electrical complex: From the source to busbar 1, from busbar 3 and the load and from the shunt unit secondary side and the series transformer primary. Fig. 7a is related to the results acquired in the computational simulation and Fig. 7b presents the same quantities tow referred to the laboratory experimental arrangement.

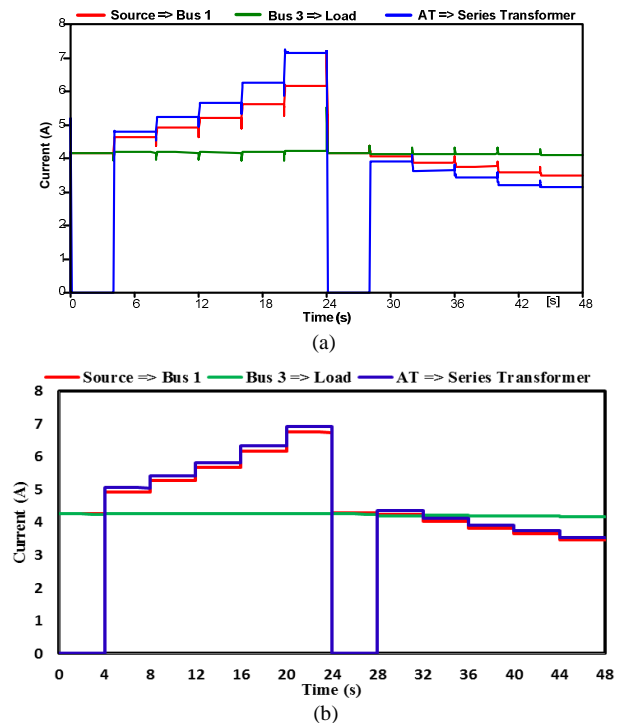


Fig. 7. Current flowing at different measuring points of the electrical complex: (a) Computationally (b) Experimentally

The values expressed in Fig. 7a and 7b is clarified in table VI.

TABLE VI. – CURRENT AT THE POINTED OUT BUSBARS

Time [s]	Computationally			Experimentally		
	Source – Bus1 [A]	Bus 3 – Load [A]	AT – P. Tr [A]	Source – Bus1 [A]	Bus 3 – Load [A]	AT – P. Tr [A]
0 to 4	4,1	4,1	0	4,2	4,2	0
4 to 8	4,6	4,2	4,8	4,9	4,2	5,0
8 to 12	4,9	4,2	5,2	5,3	4,2	5,4
12 to 16	5,2	4,2	5,6	5,6	4,2	5,8
16 to 20	5,6	4,2	6,2	6,2	4,2	6,3
20 to 24	6,2	4,2	7,1	6,7	4,2	6,9
24 to 28	4,1	4,1	0	4,2	4,2	0
28 to 32	4,0	4,1	3,9	4,2	4,2	4,3
32 to 36	3,9	4,1	3,6	4,0	4,2	4,1
36 to 40	3,7	4,1	3,4	3,8	4,2	3,9
40 to 44	3,6	4,1	3,2	3,6	4,2	3,7
44 to 48	3,5	4,1	3,1	3,5	4,1	3,5

Finally, to enlighten the apparent power involved in the process, Fig. 8 illustrate the quantity at several measuring points of the electrical complex: From the source to busbar 1, from busbar 3 and the load and from the shunt unit secondary side and the series transformer primary. Fig. 8a is related to the given results of the computational simulation and Fig. 8b presents the same quantities to the laboratory experimental arrangement. The corresponding apparent power values are given at Table VII.

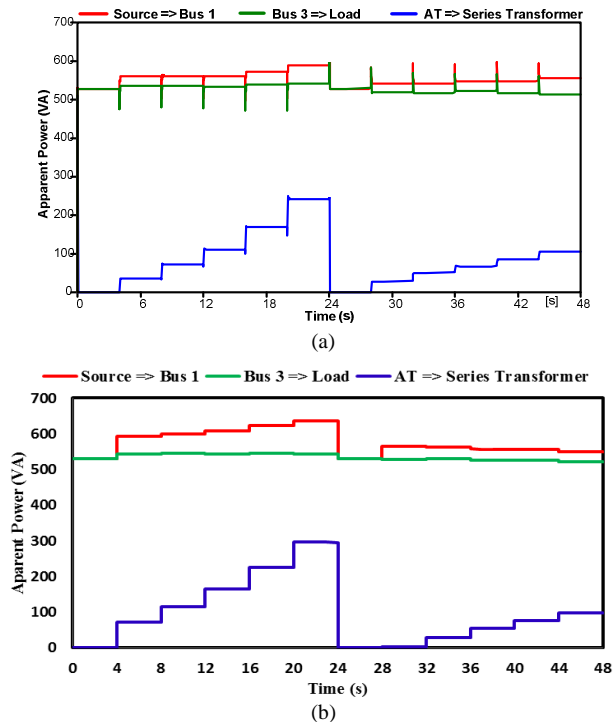


Fig. 8. Apparent power at several measuring points of the electrical complex: (a) Computationally (b) Experimentally

TABLE VII. APPARENT POWER AT THE POINTED OUT BUSBARS

Time [s]	Computationally			Experimentally		
	Source - Bus1 [VA]	Bus 3 - Load [VA]	AT - P. Tr [VA]	Source - Bus1 [VA]	Bus 3 - Load [VA]	AT - P. Tr [VA]
0 to 4	528,8	528,8	0	529,4	529,4	0
4 to 8	560,3	535,7	36,1	592,4	543,4	72,5
8 to 12	562,3	536,7	73,3	600,0	544,5	115,8
12 to 16	561,0	532,6	112,5	608,2	543,2	163,9
16 to 20	572,4	537,8	168,5	622,3	544,6	224,9
20 to 24	587,6	541,8	242,4	635,6	543,7	295,9
24 to 28	528,8	528,8	0	529,4	529,4	0
28 to 32	541,4	518,2	28,9	564,6	528,6	2,8
32 to 36	541,8	517,8	50,2	561,8	529,6	28,9
36 to 40	547,7	520,9	68,0	557,2	525,0	55,0
40 to 44	548,5	517,0	85,4	556,2	526,8	76,4
44 to 48	554,4	513,8	104,8	550,0	521,5	97,5

Table VIII presents the percentage values of the electromagnetic device in relation to the load apparent power and the imposed voltage deviation at the main feeder. S_{load} means the power supplied for the load, S_{reg} is the power portion of the load supplied by the voltage compensator and $\Delta[\%]$ express the direct relation between then.

TABLE VIII. – LOAD AND VOLTAGE COMPENSATOR APPARENT POWER RELATION

$\Delta V\%$	Computationally			Experimentally		
	S_{load} [VA]	S_{reg} [VA]	$\Delta[\%]$	S_{load} [VA]	S_{reg} [VA]	$\Delta[\%]$
0	528,8	0	0	529,4	0	0
-5	535,7	36,0	6,7	543,4	72,5	13,3
-10	536,7	73,3	13,6	544,5	115,8	21,2
-15	532,6	112,5	21,1	543,2	163,9	30,1
-20	537,8	168,6	31,3	544,6	224,9	41,3
-25	541,8	242,4	44,7	543,7	295,9	54,4
0	528,8	0	0	529,4	0	0
+5	518,2	28,9	5,6	528,6	2,8	0,5
+10	517,8	50,2	9,7	529,6	28,9	5,4
+15	520,9	68,0	13,0	525,0	55,0	10,5
+20	517,0	85,5	16,5	526,8	76,4	14,5
+25	513,8	104,8	20,4	521,5	97,5	18,7

With all above figures and tables in mind, the autores emphasizes:

- The final results highlights the voltage compensator success in keeping the load supply voltage and power consumption nearly constant all over the applied medium voltage disturbances. Therefore, it has been computationally and experimentally proved that the equipment conception here made shows effectiveness in accomplishing its purposes;
- Although the values of apparent power presented in the figures and tables associated to voltage increase compensation are positive, it must be pointed out that these values are in opposition to the voltage decrease values;
- The rated for the equipment power, under distinct situations, presents itself as a percentile of the load power, which is enlightened by the figures and tables. It implies that the electromagnetic device, for each level of voltage deviation, presents with lower values than the ones provided to the load. In this context, it is proved that as high as voltage deviation to be restore, the higher must be the equipment nominal power.

6. Conclusions

This paper has focused the physical structure of a proposed electromagnetic device based on series voltage compensation injection to restore voltage to its required levels, as defined by the regulation. A brief description of the arrangement composition and the control strategy was given and a ATPDraw time domain model has been developed to enable transient and dynamic voltage compensation studies at the occurrence of sudden voltage variation at the PCC. In order to provide means for an experimental evaluation, a laboratory arrangement has been set up utilizing existing facilities such as an autotransformer, a normal two windings transformer to represent the series unit and a manually switched procedure to define the degree of compensation to be applied. The total voltage range variation used to characterize the studies was taken from zero to 25% of voltage increase and reduction, with step changes of 5%. The computational and laboratory results here given and discussed were quite clear at showing the equipment success at performing the necessary voltage compensation. This has highlighted the proposal success at

achieving its purposes at restoring the voltage deviation. Concerning the time responses of the device, the results have shown they were instantaneous as no control loop was considered to the studies. Nevertheless, the authors would like to stress that further developments are to be carried out to define the control strategy, either mechanically or electronically, so as to cope with the type of voltage change occurring at the network. In addition to that, a real prototype of electromagnetic device is to be made to replace the experimental arrangement here utilized.

Acknowledgement

The authors express their gratitude to CAPES, CNPq and FAPEMIG by the financial sustenance towards the master and doctoral degree at Graduate Course of the Federal University of Uberlandia and other support that enabled the present research.

References

- [1] ANEEL – Brazilian Electrical Energy Agency – Electrical Distribution Procedures to the National Grid – Prodist – Module 8, 2008.
- [2] ANEEL - Brazilian Electrical Energy Agency – Resolution 505, November 26th 2001.
- [3] Banaei, M.R. ; Nahavandi, A. ; Hosseini, S.H. ; “Investigation of multi-functional DVR to improve power quality characteristic”, 6th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, 2009. ECTI-CON 2009, May 2009, Volume 01, on page 144, IEEE;
- [4] Zhengping Xi ; Parkhideh, B. ; Bhattacharya, S.; “Improving distribution system performance with integrated STATCOM and supercapacitor energy storage system”, Semicond. Power Electron. Center, North Carolina State Univ., Raleigh, NC, Power Electronics Specialists Conference, 2008. PESC 2008, IEEE;
- [5] Usha, R.P. ; Rajkumar, M. ; Reddy, S.R. ; “Voltage sag/swell compensation using Z-Source inverter based dynamic voltage restorer”, International Conference on Emerging Trends in Electrical and Computer Technology (ICETECT), 23-24 March 2011, on page 268, IEEE;
- [6] Hojo, M. ; Fukuoka, Y. ; Funabashi, T. ; Putrus, G. A. ; “Simplified power quality conditioner for dynamic voltage restoration and fault current limitation“, 10th IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change, March 29 2010, on page 1;
- [7] SANTILIO, F. P.; OLIVEIRA, J. C.; SILVA, T. V.; OLIVEIRA, A.. “An Electromagnetic Voltage Regulator Proposal throughout the Injection of Series Compensation: Physical Conception and Computational Analysis”. In: EPQU - ELECTRICAL POWER QUALITY AND UTILIZATION, 2011, Lisbon.
- [8] SANTILIO, F. P., OLIVEIRA, J. C., OLIVEIRA, A., BONELLI, A. F., BARBOSA, J. A. F., GONDIM, I. N., “Series Voltage Reinforcement throughout Electromagnetic Regulators: Computational Performance and Control” In: CBQEE – Brazilian Power Quality Conference, 2011, Cuiabá-MT – Brazil.
- [9] SANTILIO, F. P., BARBOSA, J. A. F., OLIVEIRA, J. C., OLIVEIRA, A., GONDIM, I. N., VITORETTI, L. C., “A Proposal of a Electromagnetic Voltage Regulator Using Series Voltage Injection”, 9th IEEE/IAS International Conference on Industry Application – IX INDUSCON, São Paulo-SP, November 2010.