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Computational Performance Analysis of an Electromagnetic Dynamic Voltage Restorer: Physical Conception and Operational Approaches

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Abstract. The present paper focuses an electromagnetic device to restore busbar voltages to acceptable limits using an electromagnetic arrangement conception. The new device has been called by electromagnetic dynamic voltage restorer (EDVR) due to its physical structure. As for the insertion of the degree of the series voltage compensation, two approaches are considered. The first can be recognized as a discrete procedure as the restoring voltage procedure makes use of electronically switched tap changers. The second relies on a continuous voltage variation offered by a single tap supply and a controllable electronic device. It is shown that the overall compensator idea lies on positive or negative insertion of a variable voltage in series with de feeder so as to achieve a consumer supply voltage in accordance with acceptable levels. The device comprises a traditional shunt autotransformer linked to a series transformer which provides the necessary restoring property. The paper highlights the EDVR physical structure, the control units, the ATP platform models and results associated to case studies to show the overall compensation equipment and control performance offered by the given solutions.

Key words

ATPDraw, Distribution System, Power Quality, Semiconductor Devices, Voltage Control.

1. Introduction

Nowadays, electrical energy agencies all over the world establish limits to the different power quality indicators so as to guarantee the required standard for a given supply. In this context, the Brazilian Electrical Energy Agency (ANEEL) [1] has proposed reference values for voltage variations, harmonic distortions, voltage unbalance, flicker level, power factor, amongst others.

To cope with the RMS voltage compatibility of these standards, it is quite common to find equipment which uses the classical relation of reactive power vs. voltage to restore busbar levels [2]. In this context, commercial regulators such as the capacitor banks, synchronous compensators, and electronic shunt compensators have been traditionally used. Another philosophy used to restore voltage deviation is based on series voltage reinforcement, been as addictive or subtractive. This has been also largely used. Among these arise the electronic solutions already available in market. As typical examples it can be recognize the existence of equipment such as the: DVR [3], Statcom [4], Sipcon, Power Conditioners [5], etc. These products have emerged as means to restore voltage deviation to the admissible range with a very short response time. This is the case, for instance, of the requirements to compensate for voltage sags, swells, etc. When this is to be fulfilled, the conventional mechanically taped changer transformer, the fixed capacitor bank and even the automatic units do not offer the necessary time response and the use of more advanced techniques are to be thought and to cope with this ultimate requirement. As a matter of fact, under the above conditions, only electronic devices would accomplish the system necessities. Nevertheless, the high costs involving such products, special maintenance requirements, appropriate physical installation, etc. are limiting factors.

Having the above in mind, one could recognize that the products already available are capable of attending general electrical power system demands, the search for solutions combining: operational simplicity, competitive cost, reduced maintenance needs, robustness, attractive cost-benefit relationship, fast time response, etc. is still a challenge to engineers.

Within this context, based on the additive or subtractive voltage injection compensation reinforcements, yet reconciling dynamic and steady state operational characteristics, this paper outlines a fully electromagnetic physical arrangement proposal, here denoted by Electromagnetic Dynamic Voltage Restorer - EDVR. This conception is mainly composed by two basic units, as shown in Figure 1. The first electromagnetic component is destined to extract energy from the network. It is constituted by a parallel autotransformer. The second electromagnetic power unit consists of a series transformer, responsible for the series voltage

insertion with the mains [7]-[8]. These components, as further discussed, do not require the so called full load current but only a portion of it. In addition to that, it must be emphasized that the voltage tap associated to the power deviation from the busbar is taken at a lower voltage level than the rated supply voltage.
The Figure 1 arrangement shows the regulator itself. The overall structure is given by: a parallel unit for electrical power extraction, a series voltage injection transformer and a switching module mechanism with corresponding voltage source to be inserted to achieve the required regulation purposes.

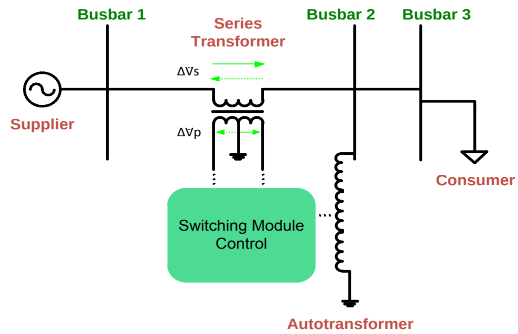


Fig. 1. EDVR physical structure

Once introduced the equipment power structure, the next step goes into the direction of establishing the series voltage variation approaches to cope with the dynamic voltage insertion to restore feeders´ voltage deviations to the acceptable levels.

2. Electromagnetic Voltage Regulator Operational Strategies

Figure 2 shows the simplified EDVR action to be fulfilled. In accordance with the illustration the additional voltage injection, positive or negative, using the series transformer polarity is enabling of restoring the voltage level deviations.

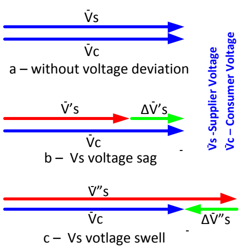


Fig. 2. The device voltage compensation principle

A. *Operational Conception 1*

The general idea associated to the proposal here considered is given in Figure 3. It can be seen that the operational strategy is fully based on the autotransformer offering a few taps and an equivalent number of electronic switches. By choosing the correct voltage level to be inserted it is quite clear that the compensation approach there referred is discrete, i.e, in steps of voltages. The tap selection, designed by switches Ch1 to Ch5 defines the value of the compensation voltage to be applied and no continuous variation is allowed as the switches firing angles are not controllable. The choice for Chpn or Chpp relies on the voltage polarity to be injected. If Chpp is to be closed, this will impose an additive voltage reinforcement, and the opposite will occur if Chpn is in operation. The Chbp switch remains closed when the consumer voltage level is in accordance to the applied voltage standard regulation.
The operational strategy under consideration is provided by monitoring busbar 1 voltage profile and constantly by a direct and constant comparison to the reference limits. If the busbar 1voltage is above or below the required range, the switching control will find the best tap to restore voltage level, as well as its polarity.

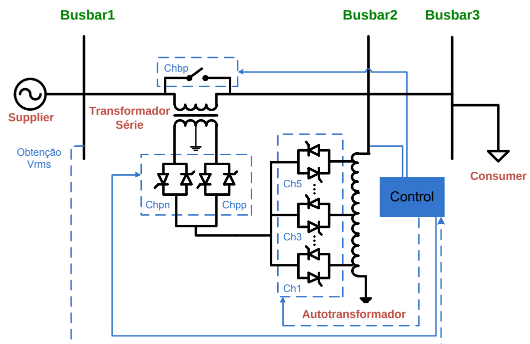


Fig. 3. Discrete tap changer physical structure conception – Proposal 1 (EDVR 1)

Using conventional ATPDraw simulator library facilities and by developing special routines throughout the MODELS platform to cope with the measurement facilities, the open-looped control unit and the specified switches; the final computational model is represented by Figure 4. This figure illustrates the required autotransformer, the series transformer, the switching module device and the open-loop control. The final software, in accordance with the used models will allow for transient, dynamic and steady state operational conditions.

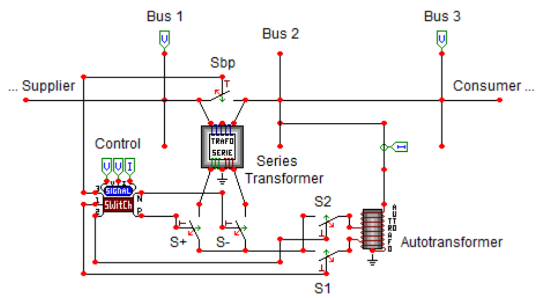


Fig. 4. The electromagnetic voltage regulator model - ATPDraw Platform - EDVR 1

B. *Operational Conception 2*

The second possibility to produce the compensating voltage is shown in Figure 5. It consists in replacing the autotransformer with few discrete taps by a single tap unit. In this case, the main concept to achieve a controllable voltage to be used by the series transformers does not came from changeable taps but by a single one, with the derived voltage being properly controlled by adjusting the GTO firing angles. To accomplish with this, the arrangement illustrates a pair of semiconductors at the autotransformer output terminals. As for the components given at the series transformer terminals, they are aimed at providing means to avoid the series voltage injection during rated voltage operation to the feeder as well as to compensate for the non-conducting period to the electronic switches.

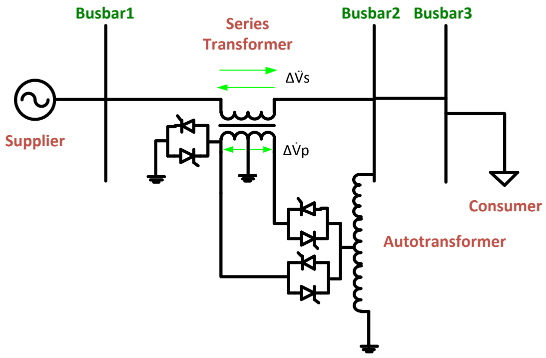


Fig. 5. Continuous voltage compensator conception – Proposal 2 (EDVR 2)

Figure 6 shows the final voltage obtained from the autotransformer, the chopped waveform to be applied to the series transformer, and the firing pulses related to the electronic switch. It can be seen that by chopping the sinusoidal voltage derived from the shunt transformer it is possible, throughout a correct definition of the firing angles α and β, to obtain a specified voltage compensation level. Therefore, it can be noted that the voltage to be inserted to the feeder can be fully controlled as for its RMS value whist the waveform is further distorted.

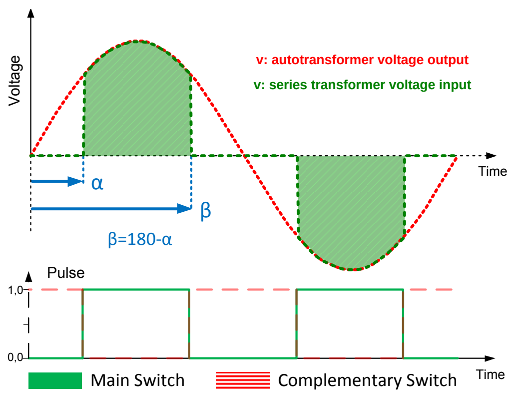


Fig. 6. The voltage compensation control strategy

Figure 7 presents the final ATPDraw time domain model. It can be clearly seen that the physical arrangement here considered is based on the use of an anti-parallel pair of switches connected to the high voltage required for regulation purposes. These are characterized by GTO commercial components due to its intrinsic operational properties.

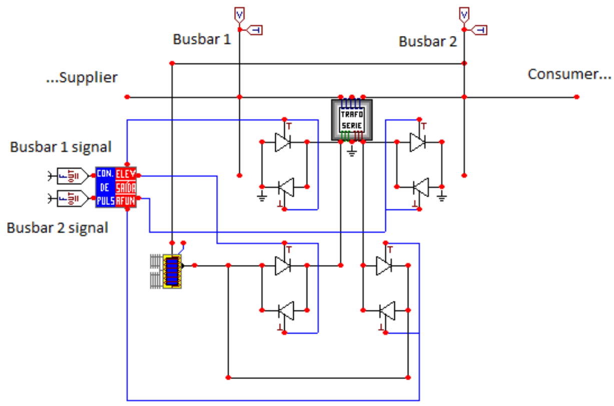


Fig. 7. The electromagnetic voltage regulator model - ATPDraw Platform - EDVR 2

3. Case Studies Characterization

The hypothetical system used in the case studies is characterized by the single-line diagram given in Figures 3 and 5. Both equivalent circuits consist in arrangement containing the: voltage supply source; the focused voltage restorer and a final consumer. Tables I and II summarize the main information concerning the hypothetical system here considered for simulation purposes and both voltage compensator devices, here defined as EDVR 1 and 2.

Table I – EDVR 1 – Main parameters

System component	Power (VA)	PF	Voltage (V)	Zsc%	Rsc%
Autotransformer	260	-	127 – with 5 discrete Taps	12,5	10,0
Series Transformer	260	-	1:1	12,5	10,0
Load	528,8	1	127	-	-

As previously stated the EDVR 1 device has been provided with voltage regulation capability given by an autotransformer output voltage having 5 taps as follows: 5%, 10%, 15%, 20% and 25%. These values have been chosen so as to match the feeder parameters and voltage conditions to be utilized as deviations from the rated conditions.

Table II – EDVR 2 – Main parameters

System component	Power (VA)	PF	Voltage (V)	Zsc%	Rsc%
Autotransformer	260	-	127/34	12,5	10,0
Series Transformer	260	-	1:1	12,5	10,0
Load	528,8	1	127	-	-

It can be seen that as for EDVR 2 only a single tap was derived from the autotransformer. As previously explained, this strategy uses a single voltage and the required compensation is provided by controlling the firing angle of the switches.

Concerning the studied cases, they are linked to a set of imposed voltage variation at the mains. The total number of situations comprising an overall period of study of 48 s has been established as described in the sequence. From the time interval from 0 to 24 seconds, it can be noticed that a gradually five steps decrement of 5% on the supply voltage has been applied. At this period of study (24 s) the voltage is restored to the original value. From this onwards, i.e., from 24-48 seconds, the voltage is steeply increased using the same values previously applied. The final voltage profile can be seen in Figure 8 and the corresponding voltage values and deviations are given in Table III.

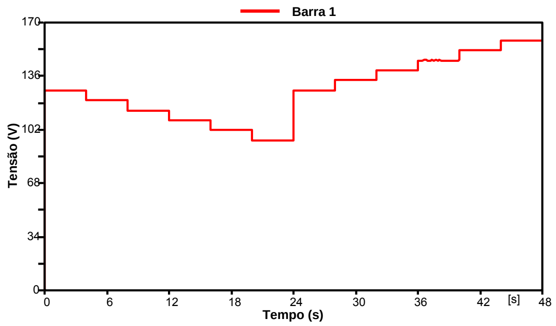


Fig. 8 - Supply voltage deviations adopted for the investigations

Table III – Voltage variations at the supply – busbar 1

Intervals	Time [s]	Voltage [V]	ΔV%
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

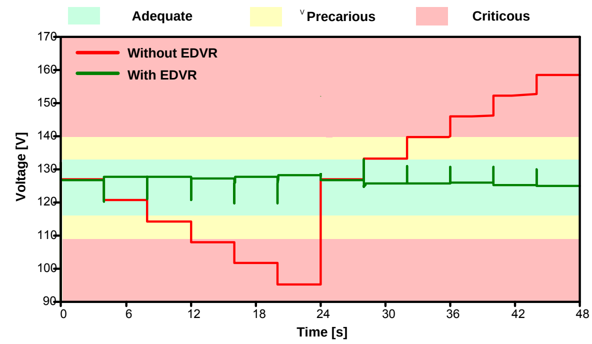
Given the above operating conditions, Table IV present the voltage values to be obtained at the autotransformer secondary so as to produce the required voltage compensation to the restore the supply to its original condition. As for the EDVR 2, in accordance with the device operation principle only a single tap will be used.

Table IV - EDVR 1 autotransfomer taps

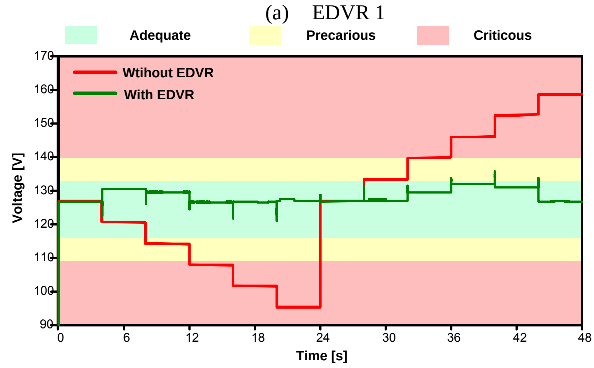
Taps	1	2	3	4	5
Voltage (V)	7,5	14,0	19,9	26,9	33,9

4. Simulations Results

Figures 9(a) and 9(b) illustrates the voltage performances at busbars 1 and 3. The results are quite clear at showing the voltage supplied by the source and the consumer input voltage related to the specified conditions chosen to the investigations. Both the EDVR 1 and 2 voltage restore strategies are given. The green, yellow and red regions highlighted show the acceptable limits considered as adequate, precarious and critical voltage values. This follows traditional regulation limits as defined by the distribution authorities. In a complementary way, Table V provides the values shown in Figure 9.



(a) EDVR 1



(b) EDVR 2

Fig. 9. Non compensated and compensated voltages profiles associated to the both EDVR 1 and EDVR 2 strategies

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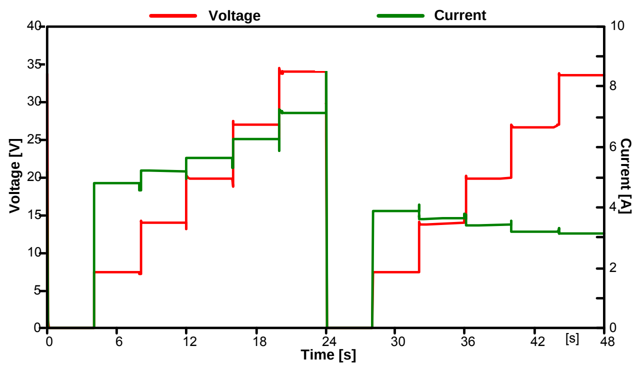
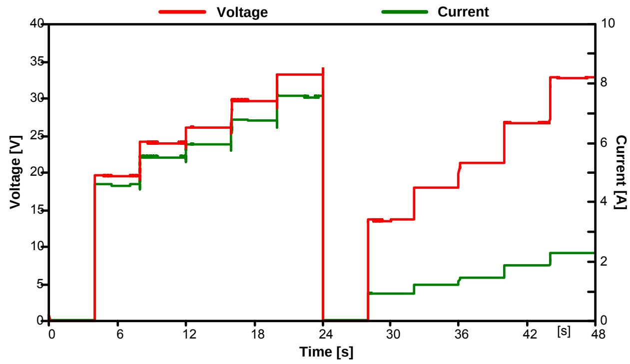
Table V – Busbar 1 and 3 Voltages

Time [s]	ΔV%	EDVR 1		EDVR 2	
		Busbar 1 [V]	Busbar 3 [V]	Busbar 1 [V]	Busbar 3 [V]
0 a 4	0	127,0	127,0	127,0	127,0
4 a 8	-5	120,7	127,8	120,7	130,3
8 a 12	-10	114,3	127,9	114,3	129,4
12 a 16	-15	108,0	127,4	108,0	126,5
16 a 20	-20	101,6	128,1	101,6	126,6
20 a 24	-25	95,3	128,5	95,3	127,2
24 a 28	0	127,0	127,0	127,0	127,0
28 a 32	+5	133,4	125,7	133,4	127,2
32 a 36	+10	139,7	125,7	139,7	129,4
36 a 40	+15	146,0	126,0	146,0	132,1
40 a 44	+20	152,4	125,6	152,4	131,0
44 a 48	+25	158,7	125,2	158,7	126,9

So as to offer an idea about the compensation devices operating load conditions, Figure 10 express the voltages and currents at the autotransformer output and the series transformer input. Figure 10(a) and 10(b) shows, respectively, the results associated with EDVR 1 and EDVR 2 strategies. Table VI gives the voltage and current values.



(a) EDVR 1



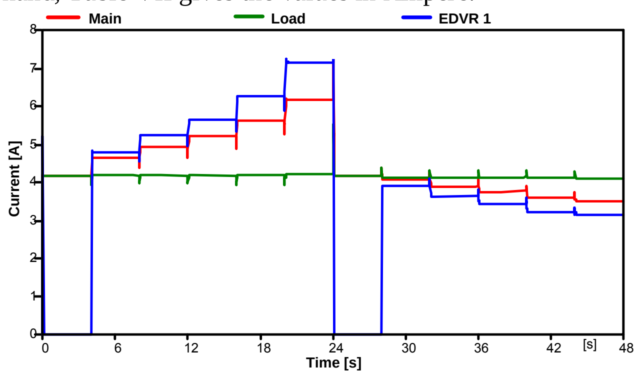
(a) EDVR 2

Fig. 10. Voltage and current at EDVR 1 - (a) and EDVR 2 - (b) - values at the autotransformer secondary and series transformer primary side

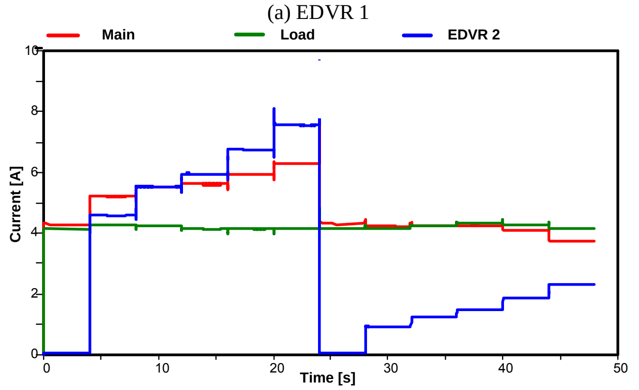
Table VI – Voltages and currents supplied by EDVR 1 and 2

Time [s]	ΔV%	EDVR 1		EDVR 2	
		Voltage [V]	Current [A]	Voltage [V]	Current [A]
0 a 4	0	0	0	0	0
4 a 8	-5	7,5	4,8	19,5	4,6
8 a 12	-10	14,0	5,2	24,0	5,5
12 a 16	-15	19,9	5,6	26,0	5,9
16 a 20	-20	26,9	6,2	29,8	6,8
20 a 24	-25	33,9	7,1	33,2	7,6
24 a 28	0	0	0	0	0
28 a 32	+5	7,4	3,9	13,5	0,9
32 a 36	+10	13,8	3,6	17,9	1,2
36 a 40	+15	19,8	3,4	21,3	1,5
40 a 44	+20	26,7	3,2	26,7	1,8
44 a 48	+25	33,4	3,1	32,7	2,3

As for the current values at the load, mains to busbar 1 and from this latter to busbar 3, they are illustrated in Figure 11(a) and (b) for the above two solutions. On the other hand, Table VII gives the values in Ampere.



(a) EDVR 1



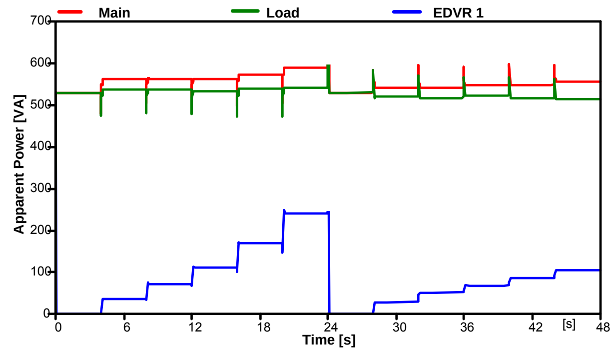
(a) EDVR 2

Fig. 11. Currents at the supply, load and compensators: (a) EDVR 1 (b) EDVR 2.

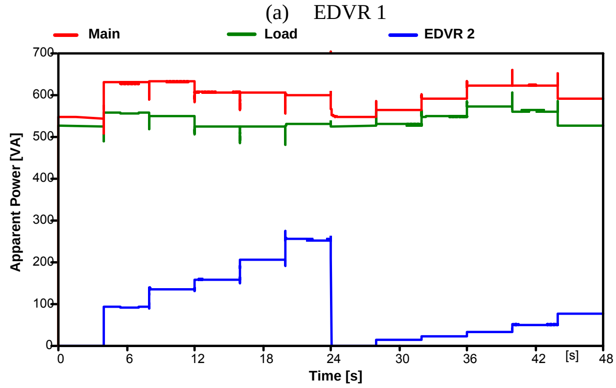
Table VII – Voltage and current at the mains, load and compensators – EDVR 1 and EDVR 2

Time [s]	EDVR 1			EDVR 2		
	Main [A]	Load [A]	EDVR 1 [A]	Main [A]	Load [A]	EDVR 2 [A]
0 a 4	4,1	4,1	0	4,1	4,1	0
4 a 8	4,6	4,2	4,8	5,2	4,3	4,6
8 a 12	4,9	4,2	5,2	5,6	4,2	5,5
12 a 16	5,2	4,2	5,6	5,6	4,1	5,9
16 a 20	5,6	4,2	6,2	6,0	4,1	6,8
20 a 24	6,2	4,2	7,1	6,3	4,2	7,6
24 a 28	4,1	4,1	0	4,1	4,1	0
28 a 32	4,0	4,1	3,9	4,2	4,2	0,9
32 a 36	3,9	4,1	3,6	4,2	4,2	1,2
36 a 40	3,7	4,1	3,4	4,3	4,3	1,5
40 a 44	3,6	4,1	3,2	4,1	4,3	1,8
44 a 48	3,5	4,1	3,1	3,7	4,2	2,3

Another information related to the compensators performance is the supplied apparent power to restore the load voltage to the required values. In this way, Figure 12 (a) and (b) illustrate the power at the load and the values supplied by the compensators. It can be clearly seen that that the compensating power is just a portion of the total load, as previously stated. The values are shown in Table VIII.



(a) EDVR 1



(b) EDVR 2

Fig. 12. Apparent power at the mains, load and compensators: (a) EDVR 1 (b) EDVR2 2.

Table VIII – Apparent power at the mains, load and compensators: EDVR 1 and EDVR 2

Time [s]	EDVR 1			EDVR 2		
	Main [VA]	Load [VA]	EDVR 1 [VA]	Main [VA]	Load [VA]	EDVR 2 [VA]
0 a 4	528	528	0	526	526	0
4 a 8	560	535	36	629	556	92
8 a 12	562	536	73	632	549	136
12 a 16	561	532	112	606	524	158
16 a 20	572	537	168	604	524	205
20 a 24	587	541	242	601	530	254
24 a 28	528	528	0	526	526	0
28 a 32	541	518	28	564	530	13

32 a 36	541	517	50	591	549	23
36 a 40	547	520	68	622	571	32
40 a 44	548	517	85	623	562	51
44 a 48	554	513	104	592	527	76

5. Conclusions

This paper has described the physical conception and the corresponding equivalent circuit of two proposals towards voltage regulation. One of them is based on discrete tap change arrangement providing voltage compensation in steps, as defined by the autotransformer taps availability. The second device uses a single voltage derived from the shunt autotransformer with a proper electronic GTO controlled operation. They have been here denominated by EDVR 1 and EDVR2. Following, models have been implemented in the ATPDraw platform and computational investigations have been carried out so as to highlight the equipment performance at restoring the voltage deviation from its original value. By selecting studies comprising successive voltage variation in stages of 5% below and above the rated value, the compensators effectiveness was computationally evaluated. The results have shown that both proposals have reached their target. In accordance with their physical principles, the first device has produced the voltage regulation in discrete way, whist the electronically controlled version has been noticed to provide a smoother compensation. Further information concerning the overall operation has been given so as to emphasize the whole operation as far as voltages, currents and powers were concerned. Nevertheless the agreement between the expected performance and results it must be stressed the subject deserves further considerations mainly at representing the hardware and software structures in terms of prototypes and laboratory validation studies.

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