AC Voltage Regulator Based on the AC-AC Buck-Boost Converter

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***Abstract*—The study and implementation of an ac voltage regulator is presented in this paper. Traditionally an ac voltage regulator is made with a transformer tap changer or with an ac-ac converter based on buck topologies, recently the developments in ac-ac converter makes feasible the implementation of voltage regulator with other topologies. In this paper is analyzed an ac voltage regulator based on the ac-ac buck-boost converter, the commutation trouble is solved with two inductors. The controller used permits to obtain a good dynamic response for large input voltage variations. The operation and brief analysis is included. Simulations and experimental results are presented.**

I. Introduction

The ac voltage regulator is traditionally made with a tapped transformer (Fig. 1), but the response of the system is too slow. This is because the tap is changed only during the zero crossing of the load current, due to SCR semiconductors are used; but also because normally the rms value is computed to determine the tap transition. Additionally many taps are required in order to have a good percentage of regulation.

In order to reduce the number of taps, in [1] was proposed a method to obtain a low percentage of regulation with the optimum number of taps, but the response system is still slow. And the system becomes too complex.

In [2-4] have been proposed different topologies that permit to obtain a better dynamic response, because they are operated at high frequency. These schemes are based on buck type ac-ac converters, and then in all these cases it is strictly required a transformer in order to regulate a low voltage (Fig 2). Also a complex switch commutation is considered (four steps).

In [5] a buck topology of an ac-ac converter was presented that eliminate the typical commutation troubles of ac-ac converter in a simplified way. This idea can be easily extrapolated to other type of converter, like ac-ac boost converter, and so on. But as in dc-dc converters the use of no buck type converters are more difficult to control, so the use of boost or buck-boost converters have not been studied.

In this paper is presented an ac voltage regulator based on the buck-boost ac-ac converter. With this topology no transformer is required, because the topology can reduce and boost the voltage as it is needed. The commutation trouble is solved splitting the inductor in two. Additionally, it is used a controller that permits the fast response of the system, and the final implementation is relatively simple.

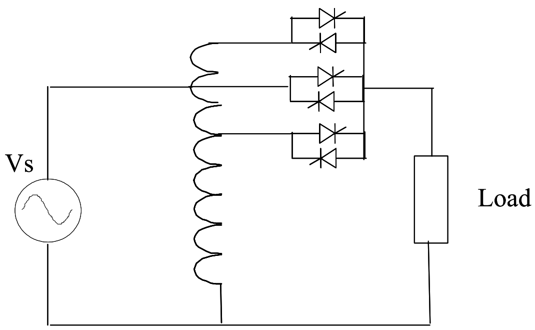
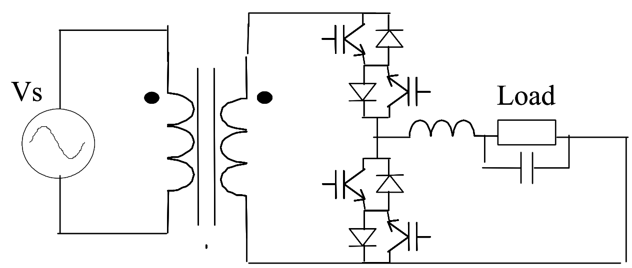
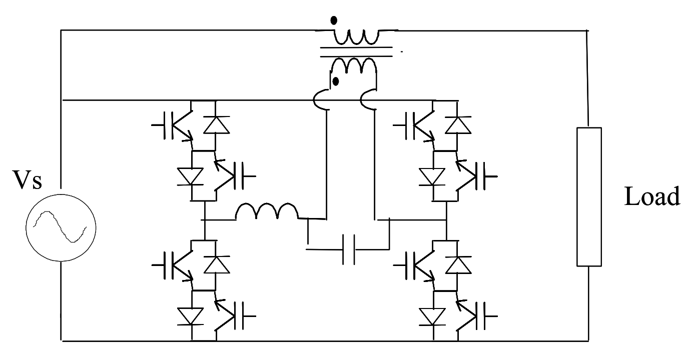


Fig. 1. Traditional voltage regulator based on a tap changer.



a) Scheme one



b) Scheme two

Fig. 2. Voltage regulators based on ac-ac buck converter.

II. AC-AC CONVERTERS

The implementation of ac-ac converters is more complex than other type of converters, this is because the operation complexity of the semiconductors. This is due to the commutation troubles in the ac-ac converters. According to Fig 3.a, the switches S_1 and S_2 can not be turned on at the same time, because a short circuit can be produced, then a blanking time should be introduced on the control signal of the switches (like in voltage feed inverters); however, as the load can be inductive (or at least a filter is used) the blanking time on the control signals can not be introduced, because a voltage spike occurs due to the inductive load (always a free wheeling path must be provided with inductive loads). Apparently this makes no possible the implementation of high frequency ac-ac converters.

In [6] was proposed a method to solve the commutation trouble, but it is required to sense voltage and currents to determine the four steps sequence to turn on and off the actual switches of the practical implementation (Fig. 3.b). The four step sequence to turn off the switches $S_{1a\text{-}b}$, and turning on the switches $S_{2a\text{-}b}$ for a positive voltage and current in a practical circuit is as follows:

- The switches $S_{2a\text{-}b}$ are off, and the switches $S_{1a\text{-}b}$ are on, then
- The switch S_{1b} is turned off (step 1),
- The switch S_{2b} is turned on (step 2),
- The switch S_{1a} is turned off (step 3),
- The switch S_{2a} is turned on (step 4).

A different sequence is used for negative current or voltage; this makes a complex implementation of the ac-ac converter.

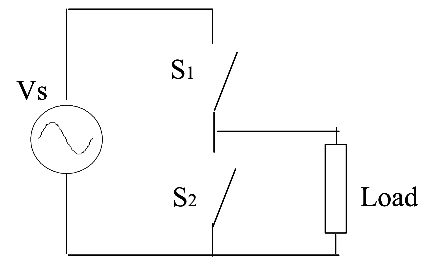
In [5] a buck ac/ac converter was proposed, that does not require the complex circuit to determine the four step sequence to turn on and off the switches, only an overlapping of the control signal of the switches is required (like in current feed inverters). This is made with another type of four quadrant switch.

This idea can be extrapolated to other topologies, like boost and buck-boost topology. But the use of boost and buck-boost topologies is more difficult to implement in the control point of view, so these kinds of converters have not been studied.

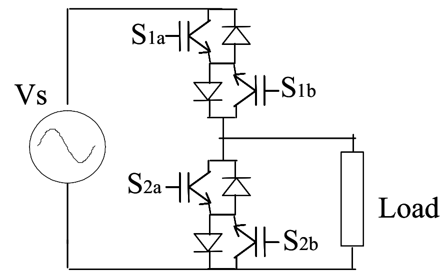
III. THE AC VOLTAGE REGULATOR

In ac voltage regulators it is required to compensate sags and swells, so it is necessary the bucking and boosting capability. The topology that permits this capacity is the buck-boost converter. The simplified circuit diagram of this converter is shown in Fig 4.a. In order to avoid the commutation trouble the inductor is separated in two, and assuring that the current will flow in just one direction. A four quadrant switches are used, but a small variation is made in order to assure the current flow in one direction. The final topology is shown in Fig 4.b. The inductors in the figures are equal, that is $L_1=L_2=L$.

The IGBTs are turned on in a complementary way, but a small overlapping must be introduced to permit continuity on the inductor current.

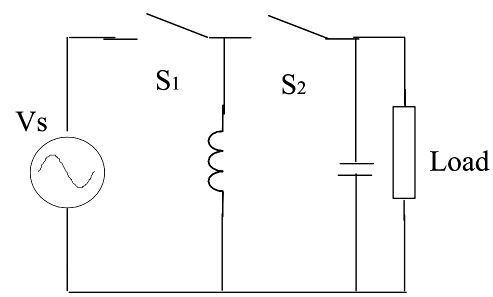


a) Simplified circuit

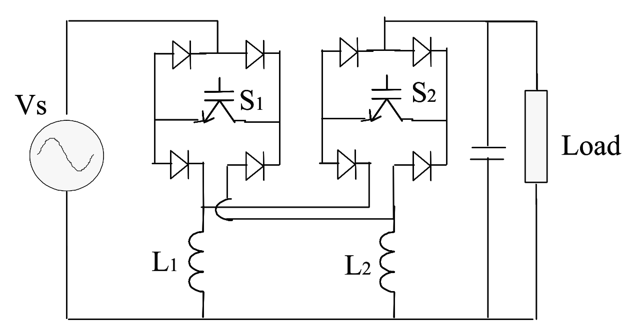


b) The circuit with four quadrant switch

Fig. 3. The high frequency AC-AC converter.



a) Simplified circuit



b) The implemented circuit

Fig. 4. The AC-AC buck-boost converter.

The converter during the switch transition operates as follows:

1. Assuming that the inductor L_1 has current and the input voltage is lower that the output voltage, and the switch

S_1 is on, the current is going through the semiconductor S_1

2. The switch S_2 is turned on, and due to the diodes next to S_2, there are no conduction between the switches, and the current still going through S_1
3. When the switch S_1 is turned off, there is a free wheeling path through the switch S_2. Then a safe transition is performed.

For different voltages and currents, always a safe transition will occurs, also if the transition is for turning off the switch S_2 and turning on the switch S_1. Only it is necessary to overlap the control signal of the switches.

A. *Analysis of the converter*

In order to analyze the converter, an average model is considered and the simplified circuit of the buck-boost converter is considered (Fig. 4.a); the averaged model considered is shown in Fig. 5. Using the phasor concept, the system is analyzed. The gain function of the converter is then:

$$\frac{V_o}{V_s} = \frac{-d}{(1-d) + \frac{\omega^2 LC}{(1-d)} + \frac{j\omega * L}{R*(1-d)}} \quad (1)$$

Where: V_o is the output voltage or load voltage.
V_s is the input voltage
d is the duty cycle
w is frequency
R is the load
L and C are the passive elements of the circuit

This gain is graphed in Fig. 6, it is shown for different values of the duty cycle, that was changed in steps of 0.1, starting in 0.1 and finishing at 0.9. As can be seen the converter can boost/buck the input voltage. In order to assure a good operation the value of the inductance and capacitance must be selected to avoid resonances of the system as it is shown in the figure.

It is important to notice that to obtain an ac voltage a constant duty cycle is required, and the output voltage will follow the input voltage form, but with the difference that the amplitude can be modulated by the duty cycle.

IV. The Controller

An important part of the system is the controller, as an ac voltage regulator is implemented, a good performance is required. Traditionally a circuit to obtain the rms value of the output voltage is used, but this method is slow.

In this paper a different method was used, an amplitude detector is considered, and then a PI controller. A block diagram of the controller is shown in Fig. 7.

The amplitude detector is based on trigonometry. The output voltage is sensed, and introduced to a 90 degrees lagging circuit, then a cosine function is obtained, after the square of the sine and cosine functions are obtained; finally to obtain the representation of the amplitude value, the result of the squared functions are added. So the result of the operation is a constant value, which depends of the square peak value of the output voltage. This method permits to calculate the required peak output voltage in a fast manner, so a good response is obtained.

The controller used is a traditional PI compensator; this compensator was sintonized on line, first in simulation, and after experimentally. The output of the compensator is introduced to a classic PWM circuit.

V. Simulation and Experimental Results

A prototype was designed and built, and in order to verify the performance of the system some simulations and test to the prototype were performed. The parameters are Vs=120V $\pm$ 20%, Vo=120V.

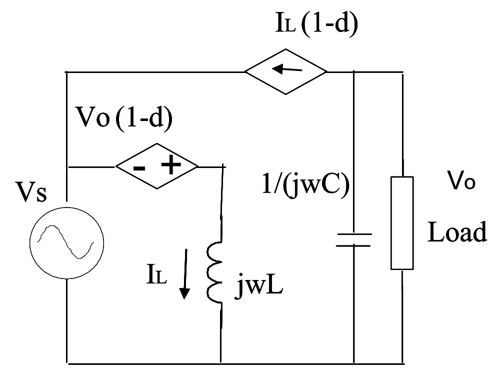


Fig. 5. The simplified model of the AC-AC buck-boost converter.

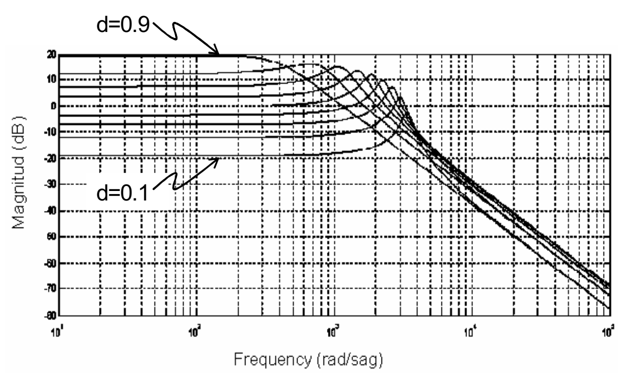


Fig. 6. Function gain of the converter.

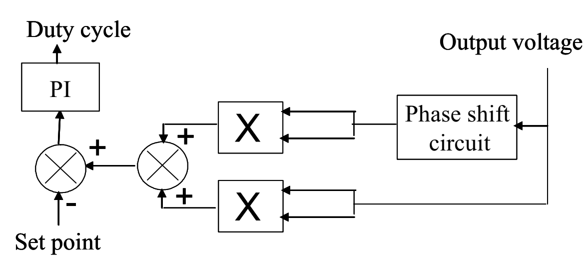


Fig. 7. Block diagram of the controller.

In Figs. 8-9 the simulation of the system are shown. In Fig. 8 the open loop system is simulated; the input voltage, output voltage and duty cycle are shown; as it can be observed the output voltage is higher than the input voltage, because of the duty cycle.

In Fig. 9 is shown the performance of the amplitude detector under a voltage variation, as it can be observed a good performance is obtained.

In Figs. 10-13 are shown the experimental results of the system. In Fig. 10 is shown the system for a boosting operation, the input voltage is 88 V_{rms} and the converter is making the boosting function ($Vo=120V_{rms}$), this is made using the corresponding duty cycle.

In Fig. 11 is shown the system for a bucking operation, the input voltage is 132 V_{rms}, as can be observed the output voltage is lower that the input voltage ($Vo=120V_{rms}$), also the controller permit to make the correction properly.

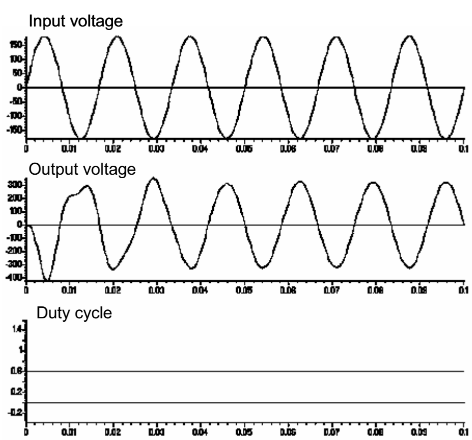


Fig. 8. Simulations open loop. Input voltage, Output voltage, duty cycle.

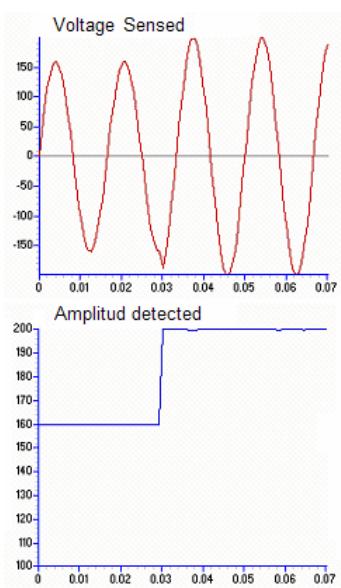


Fig. 9. Simulation of the amplitude detector under a voltage variation.

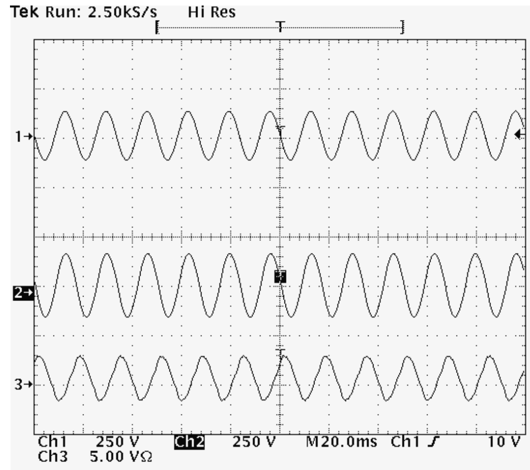


Fig. 10. Experimental results for the boosting function. Up to down: Input voltage, output voltage and input current.

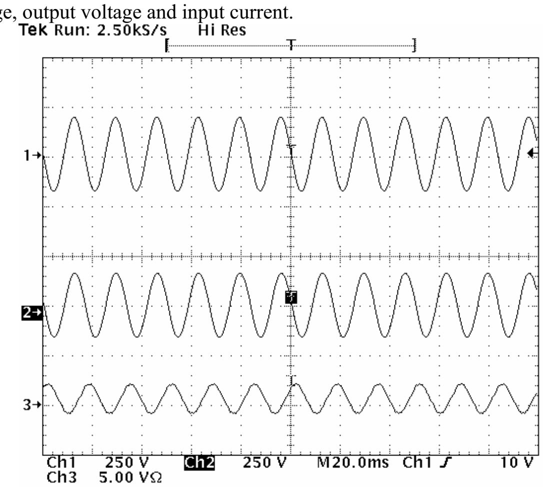


Fig. 11. Experimental results for the bucking function. Up to down: Input voltage, output voltage and input current

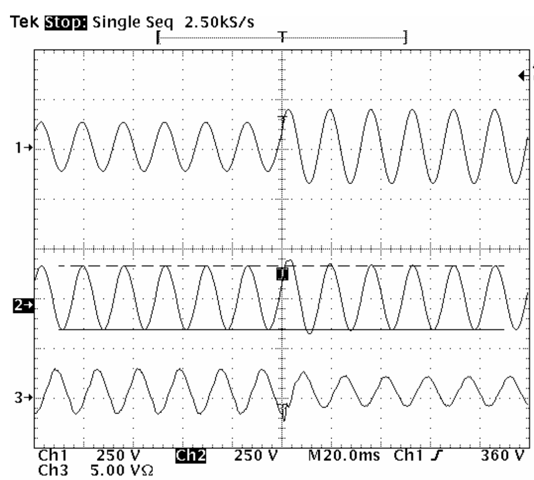


Fig. 12. Experimental results for an input voltage variation. Up to down: Input voltage, output voltage and input current.

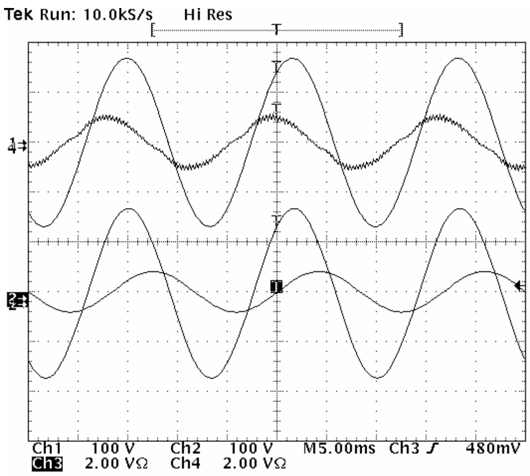


Fig. 13. Experimental results for inductive operation. Up to down: Input current and voltage, Output current and voltage.

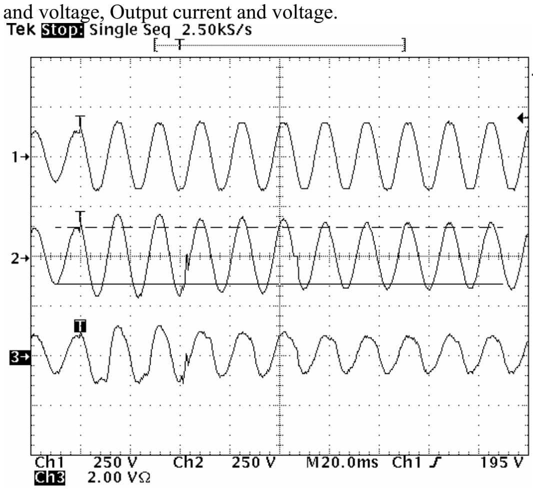


Fig. 14. Operation of a traditional voltage regulator under input voltage variation. Up to down: Input voltage, output voltage and input current.

In Fig. 12 is shown the operation of the system under an input voltage variation, as can be observed the converter has a good performance under the variation. The input voltage changes between $88V_{rms}$ to $132V_{rms}$. Also it can be observed a good percentage of regulation.

In Fig. 13 is shown the operation of the system with an inductive load, as can be observed the system operates properly under this type of loads.

As a comparison, in Fig. 14 is shown the experimental results of a traditional voltage regulator based on tap changer, as it can be observed the system has a very slow response. And also a not so good percentage of voltage regulation is obtained

VI. Conclusions

The study and implementation of an ac voltage regulator based on the ac-ac buck-boost converter is presented in this paper. Traditionally an ac voltage regulator is made with a transformer tap changer or with an ac-ac converter based on buck topologies, however the recently developments in ac-ac converter makes feasible the implementation of ac voltage regulators with other topologies.

The proposed ac voltage regulator based on the ac-ac buck-boost converter has a good performance, because the controller permits to do it. Fast dynamic response is obtained and also a good percentage of the voltage regulation.

Simulation and experimental results are presented.

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References

[1] J. Faiz, B. Siahkolah. “New Solid-Sate Onload Tap-Changers Topolofy for Distribution Transformers”. *IEEE Transactions on Power Delivery, Vol 18, No 1*, January 2003. pp 136-141

[2] E. Raaijen, R.K. Jardan, G.J. Ruumpol, J. Sieben. “An efficient and Economical Active AC Line Conditioner” IEEE IECON 95. pp.664-670.

[3] BH Kwon, BD Min, JH Kim. “Novel Conmutation Techique of AC-AC Converter” *IEE Proc. Electr. Power Applications*, Vol 145, No 4, July 1998, pp.295-300.

[4] C. Schalkwyk, H.J. Beukes, H.T. Mouton. “An AC to AC Converter Based Voltage Regulator” IEEE Africon 2002, pp. 719-722.

[5] C. Petry, J. Fagundes, I. Barbi. “New AC-AC Converter Topologies” IEEE International Symposium on Industrial Electronics ISIE’03 , pp 427-431.

[6] PN Enjeti, S Choi. “An Approach to Realize Higher Power PWM AC Controller” IEEE Applied Power Electronics Conference and Exposition APEC’93, pp 323-327