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# Interconnection of electrical energy storage systems for power quality improvement

M. Brenna, G.C. Lazaroiu, R. Rotaru, E. Tironi

***Abstract*--Energy storage is playing an increasingly important role in the electrical power system thanks to the development and advance in various energy storage and power electronics technologies in recent years. The paper inquires into energy storage examining electrical energy storage devices, especially supercapacitors. Relative on these energy storage concerns, different dc/dc converters were analyzed using the EMTP/ATPDraw program to observe their behavior on different parameters such as: duty cycle, switching frequency or capacitance. Moreover the effects of the switching frequency variation have been analyzed.**

***Index Terms*— boost converter, buck converter, DC/DC converters, supercapacitors, THD**

## I. Introduction

THE energy storage is playing an increasingly important role in the electrical power system thanks to the development and advance in various energy storage and power electronics technologies in recent years. On the other hand, the increase in electrical load, the tendency to operate the power system closer to its limit, and the associated reliability issues are driving the development of the energy storage technologies and their applications [1].

The dc/dc converters have attracted special interest in various fields related to the alternative and renewable energy generation and power supplies of small-scale distributed type photovoltaic generation system (PVGS), fuel cell generation system (FCGS), battery and supercapacitor energy storage systems [2].

Relative on these energy storage concerns it were simulated different dc/dc converters, using the ATP Program to observe their behavior on different parameters variations, such as: duty cycle, switching frequency, and capacitance. The simulation are realized in particular on buck and boost chopper, two different converters that will form the device used in energy storage buck-boost.

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## II. Electrical Energy Storage

Supercapacitors are electrochemical capacitors that have an unusual high energy density when compared to common capacitors, typically on the order of thousands of times greater than a high-capacity electrolytic capacitor.

The electrical double layer is a structure that describes the variation of electric potential near a surface, and has a large bearing on the behavior of colloids and other surfaces in contact with solutions and solid state fast ion conductors.

The analogue in plasma is the double layer. An electrolytic capacitor is a type of capacitor typically with a larger capacitance per unit volume than other types, making them valuable in relatively high-current and low-frequency electrical circuits.

This is especially the case in power-supply filters, where they store charge needed to moderate output voltage and current fluctuations, in rectifier output, and especially in the absence of rechargeable batteries that can provide similar low-frequency current capacity [3, 4].

Supercapacitors can be viewed as two non-reactive porous plates suspended within an electrolyte, with a voltage applied across the plates. The applied potential on the positive plate attracts the negative ions in the electrolyte, while the potential on the negative plates attracts the positive ions.

This effectively creates those two layers of capacity storage, one where the charges are separated at the positive plate, and another at the negative plate.

Supercapacitors are normally designed and optimized in dedicated applications. The charging and discharging times are decided accordingly.

Commercial capacitors are designed for specific purpose such as switchgear, power quality, high speed photography and repetitive applications as shown in Table I.

Table I Application oriented charge and discharge times of supercapacitors

| Applications | Charging time | Discharging time |
|---|---|---|
| Switchgears | 60 - 120 s | 20 - 50 s |
| Power Quality | 50 - 100 s | 10 ms-10 s |
| Flash lamps | 10 - 20 s | 1 -100 ms |
| Pulsed | <1.0ms | > 1.0 ms |

Supercapacitors have relatively longer charge and discharge times; at least > 1.0 ms so they are not good for storing microsecond lightning pulses. However, normal capacitors may be considered as an alternative. The dc batteries, whatsoever, are absolutely unable to store lightning surges [5]. Supercapacitors are much more suitable for leveling voltage/current sags created by short circuit faults on power system. Thus the primary applications of supercapacitors are more attractive for, vehicles and power quality area.

## III. DC/DC CONVERTERS

In recent years, the higher efficiency and the more advanced power conversion, the energy utilization equipment, the variety of circuit topologies of the soft switching dc/dc power converter are spread used. A dc/dc converter is a device that accepts a dc input voltage and produces a dc output voltage [6, 7]. Typically the output produced is at a different voltage level than the input.

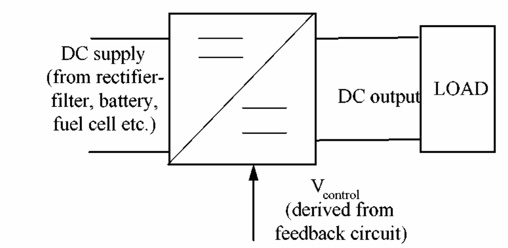


Fig. 1. General block diagram of a DC-DC converter.

### A. Buck (step-down) converter

The model implemented in ATP Program is shown in Fig. 2.

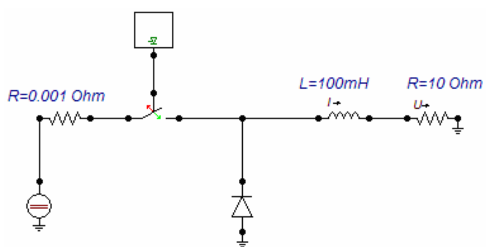


Fig. 2. Model of the buck chopper implemented in ATPDraw.

To evaluate the quality of the converter output waveform can be expressed by using the Fourier analysis data to calculate the total harmonic distortion (THD) in relative values for voltage using (1).

$$THD_V = \frac{\sqrt{V_1^2 + V_2^2 + V_3^2 + \ldots + V_n^2}}{V_0} \qquad (1)$$

Firstly, the influence of the duty cycle variation on the total harmonic distortion of the output voltage is investigated. The duty cycle $\delta$ is varied between 0.1 and 0.9, and the switching frequency is set $f_{sw}$ =1000 Hz. The inductance is set to 100mH. The total harmonic distortion in relative values is reported in Table II [8].

TABLE II. VARIATION OF ($THD_V$) WITH THE DUTY CYCLE IN RELATIVE VALUES

| δ | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|
| $THD_v$ | 3.67 | 3.26 | 2.85 | 2.44 | 2.04 | 1.63 | 1.22 | 0.81 | 0.41 |

The variation of THD values with the duty cycle $\delta$ is shown in Fig. 3. According to Fig. 3, the dependence between THD and duty cycle is a linear one because the continue component on which we divided the square root is a bigger one.

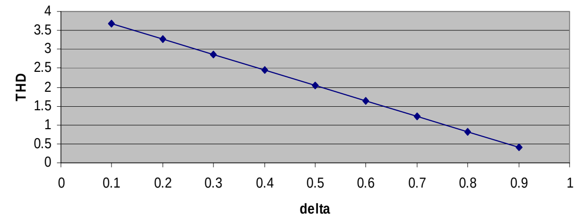


Fig. 3. Variation of the $THD_V$ with the duty cycle $\delta$.

The simplest way to reduce a DC voltage is to use a voltage divider circuit, but voltage dividers waste energy, since operated by bleeding off excess voltage as heat; also, output voltage isn't regulated (varies with input voltage). Admittedly that buck chopper is a step-down converter, on the other hand, can be remarkably efficient (easily up to 95% for integrated circuits) and self-regulating, making it useful for tasks.

Therefore, can be observe that the output voltage is lower on $\delta$ =0.1 that means a directly proportionality between output voltage waveform and duty cycle $\delta$, Fig. 4.

The quality of the output waveform of the buck chopper is tending to be a very good one when the constant $\delta$ is approaching to value $\delta$=1, also the ripple is becoming smaller but on the same time the output voltage is increased. Fig. 5 shows the variation of the output voltage and input current for the duty cycle $\delta$=0.9, $f_{sw}$=1000Hz, L=100mH.

Increasing the duty cycle $\delta$ will slow down the stability, the time to get to stability point will be bigger such as: for $\delta$ =0.1 the output voltage waveform is stabilized after 0.03s (Fig. 4), and for $\delta$ =0.9 after 0.04s (Fig. 5).

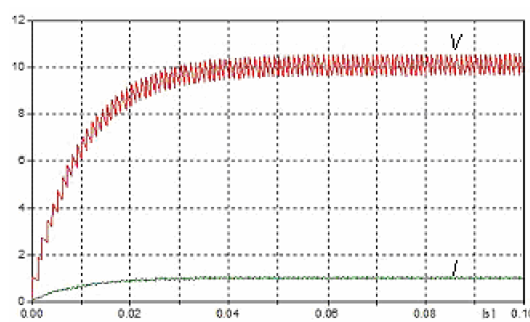


Fig. 4. Variation of the voltage and current for $\delta$=0.1, $f_{sw}$=1000Hz, L=100mH

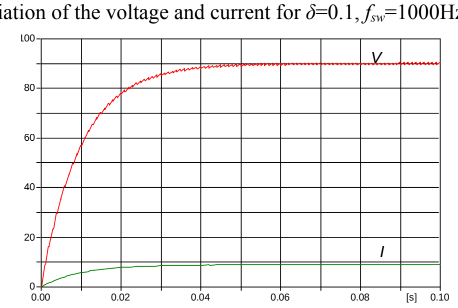


Fig. 5. Variation of the voltage and current for $\delta$=0.9, $f_{sw}$=1000Hz, L=100mH

Secondly, the influence of the switching frequency variation on the total harmonic distortion of the output voltage is investigated. The switching frequency is varied between 1kHz and 10kHz, while the duty cycle is set $\delta$=0.5. The variation of $THD_v$ with the switching frequency is shown in Fig. 6.

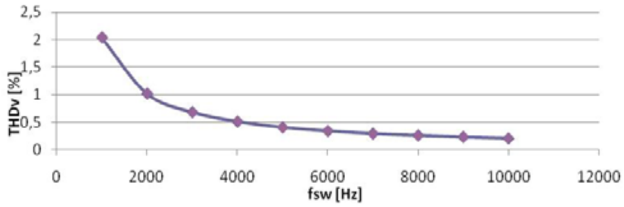


Fig. 6. Variation of the $THD_V$ with the switching frequency $f_{sw}$.

Fig. 6 shows that increasing of the switching frequency, the $THD_v$ becomes lower, which means a higher quality of output waveform.

Based on the harmonic distributions, on lower switching frequency $f_{sw}$ =1000Hz, the fundamental harmonic is almost 50V, while on $f_{sw}$ =5000Hz it is becoming 250V, at $f_{sw}$ =10000Hz is 500V, which means it is a directly proportionality between switching frequency and fundamental harmonic.

Fig. 7 shows the variation of the output voltage and input current for the duty cycle $\delta$=0.5, L=100mH and $f_{sw}$=1000Hz, while Fig. 8 shows the variation of the output voltage and input current for the duty cycle $\delta$=0.5, L=100mH and $f_{sw}$=10000Hz.

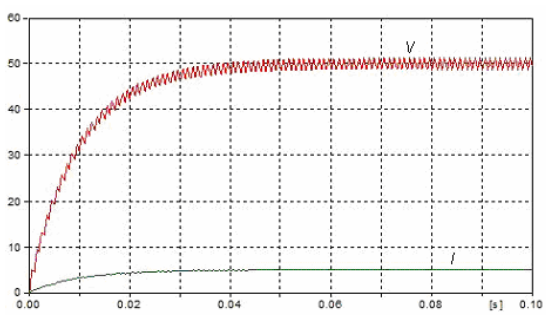


Fig. 7. Variation of the voltage and current for $\delta$=0.5, L=100mH, $f_{sw}$=1000Hz

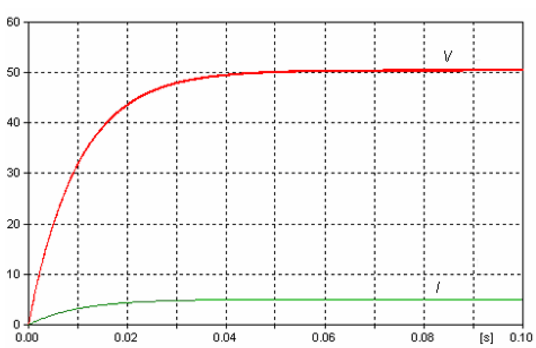


Fig. 8. Variation of the voltage and current for $\delta$=0.5, L=100mH, $f_{sw}$=10000Hz

## B. Boost (step-up) converter

The boost converter (step-up converter) is a power converter with an output dc voltage greater than its input dc voltage. The model implemented in ATP Program is shown in Fig. 9.

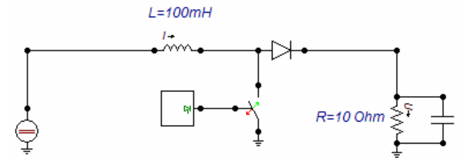


Fig. 9. Model of the buck chopper implemented in ATPDraw.

As for the buck converter, the investigation of the duty cycle and switching frequency influence on the THDv are considered. In addition, the variation of the THD with the capacitance C of the capacitor is considered.

The total harmonic distortion (THD) in relative values is reported in Table III.

TABLE III. VARIATION OF ($THD_V$) WITH THE DUTY CYCLE IN RELATIVE VALUES

| δ | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|
| $THD_v$ | 0.41 | 0.82 | 1.22 | 1.63 | 2.04 | 2.45 | 2.86 | 3.31 | 3.80 |

The variation of THD values with the duty cycle $\delta$ is shown in Fig. 10. The variation of THD values with the duty cycle δ is a linear one, as for the case of the buck converter. The quality of the output waveform of the buck chopper is tending to be a very good one when the constant $\delta$ is approaching to value $\delta$=0.1, also the ripple is becoming smaller but on the same time the output voltage is increased.

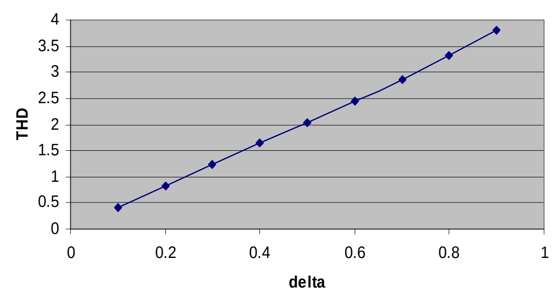


Fig. 10. Variation of the $THD_V$ with the duty cycle $\delta$.

Increasing the duty cycle $\delta$ will slow down the stability, the time to get to stability point will be bigger such as: for $\delta$ =0.5 the output voltage waveform is stabilized after 0.1s (Fig. 11), and for $\delta$ =0.8 after 0.6s (Fig. 12).

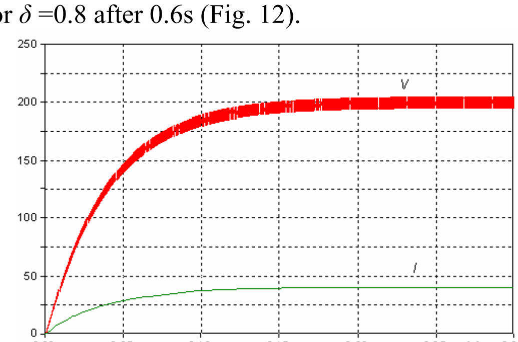


Fig. 11. Variation of the voltage and current for $\delta$=0.5, $f_{sw}$=10000Hz, L=100mH

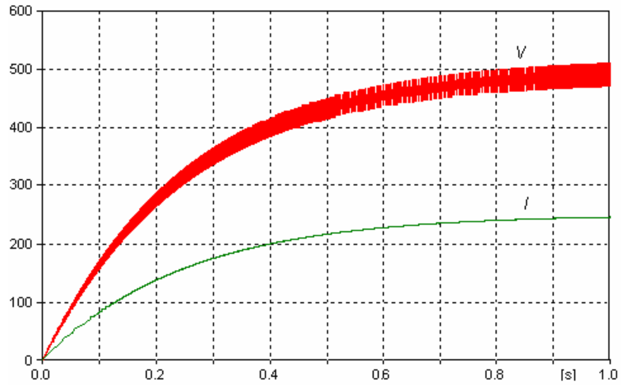

Fig. 12. Variation of the voltage and current for $\delta$=0.8, $f_{sw}$=10000Hz, L=100mH

Secondly, the influence of the switching frequency variation on the total harmonic distortion of the output voltage is investigated. The switching frequency is varied between 1kHz and 10kHz, while the duty cycle $\delta$ is set $\delta$=0.5. The variation of $THD_v$ with the switching frequency is shown in Fig. 13. It can be observed that after a frequency of $f_{sw}$=4000Hz, the dependence between THD and switching frequency is not changing very much.

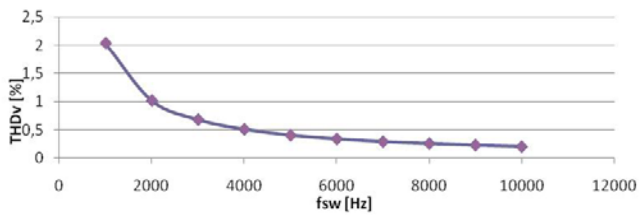

Fig. 13. Variation of the $THD_V$ with the switching frequency $f_{sw}$.

Fig. 14 shows the variation of the output voltage and input current for the duty cycle $\delta$=0.5, L=100mH and $f_{sw}$=1000Hz, while Fig. 15 shows the variation of the output voltage and input current for the duty cycle $\delta$=0.5, L=100mH and $f_{sw}$=10000Hz.

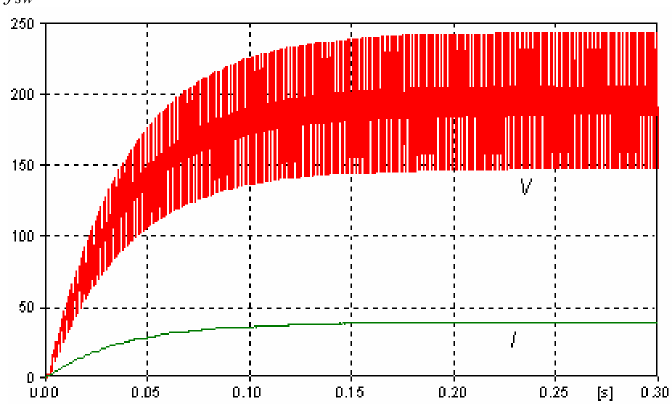

Fig. 14. Variation of the voltage and current for $\delta$=0.5, L=100mH, $f_{sw}$=1000Hz

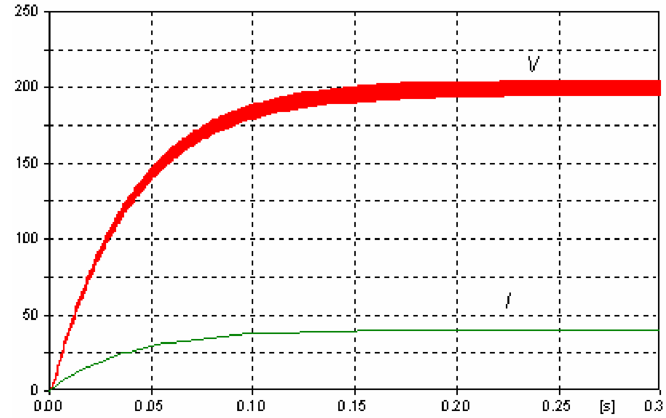

Fig. 15. Variation of the voltage and current for $\delta$=0.5, L=100mH, $f_{sw}$=10000Hz

The time to get to stability is almost the same and is not changing with the increase of the switching frequency. It can be observed that the ripple factor, also the amplitude, decrease by increasing the switching frequency.

When the duty cycle is kept constant $\delta$=0.5 and the switching frequency is set $f_{sw}$=1000Hz, the capacitance is varied between 100µF and 3000µF, with a step of 300µF. The variation of THD values with the capacitance *C* is shown in Fig. 16.

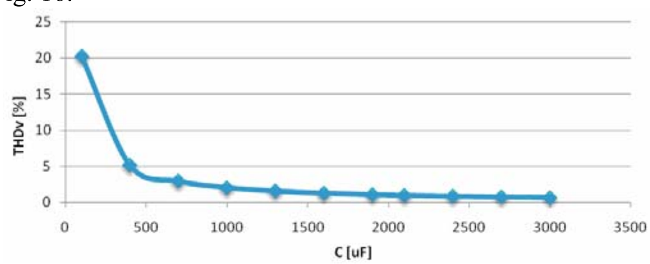

Fig. 16. Variation of the $THD_V$ with the capacitance *C*.

It can be observed that for a capacitance greater as 700µF, the dependence between THD and the capacitance is not so important. The explanation is the fact that the efficiency is not a linear one. The ripple factor decreases with the increase of the capacitance.

For δ=0.5 and for a switching frequency of 1000Hz, the variation of the voltage and current wih respect to the capacitance C are illustrated in Fig. 17 and Fig. 18.

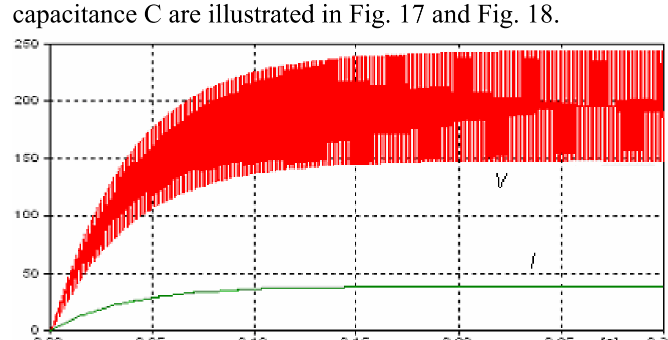

Fig. 17. Variation of the voltage and current for $\delta$=0.5, L=100mH, $f_{sw}$=1000Hz and C=100 µF.

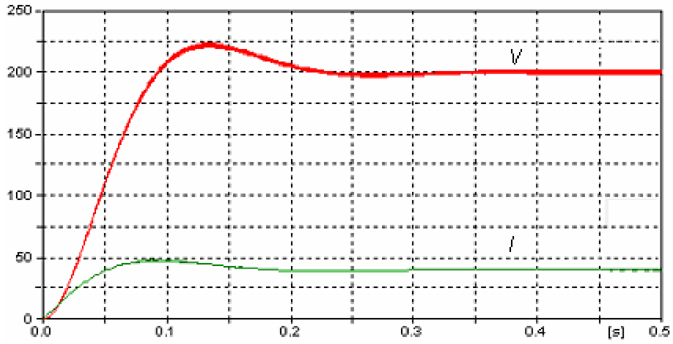


Fig. 18. Variation of the voltage and current for $\delta$=0.5, L=100mH, $f_{sw}$=1000Hz and C=3000 µF.

## IV. Conclusions

The energy storage is playing an increasingly important role in the electrical power system thanks to the development and advance in various energy storage and power electronics technologies in recent years. On the other hand, the increase in electrical load, the tendency to operate the power system closer to its limit, and the associated reliability issues are driving the development of the energy storage technologies and their applications.

The simulations realized using the ATP Program on the dc converters for different duty cycle, switching frequency, and capacitance show how the characteristics of these two choppers can be varied. For the buck converter, variation of the duty cycle decreases the ripple. For the boost it has a different variation because the ripple is also influenced by capacitance value giving the boost operation. If a decrease of ripple, maintaining the switching frequency constant, is desired the buck will need a higher duty cycle; the boost will need a lower duty cycle without varying the capacitance, or 0.5 value if the capacitance is increased.

Referring to the operation of these converters during the switching frequency keeping on the duty cycle at the medium value it can be observed that the ripple factor decreased if the switching frequency it is augmented. Therefore, in the future and also today they are used converters on high switching frequency even to improve power quality on energy storage.

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## VI. Biographies

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