Size and Cost Reduction of the Energy - Storage Capacitors

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Abstract— **In order to feed a VRM from the AC line, several voltage–reduction steps are used. In this power chain, energy storage is required. This paper pretends to select the best voltage to store the energy and also to select the point in which to place the storage capacitor, looking for a reduction of the size and cost of this capacitor. To comply with this aim, two configurations of the power chain have been compared as well as different output voltages for each power block. The proposed analysis has resulted in some practical recommendations about how to handle the main factors which determine the size and cost of the storage capacitors.**

I. INTRODUCTION

Energy storage in capacitors is a common requirement in many switching converters applications. AC/DC power supplies are one of the more widely used applications of switching converters. In these type of circuits energy storage is also required and it can be implemented placing the storage capacitor at several points among the different conversion blocks (see Fig.1).

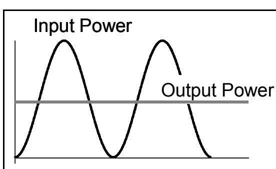
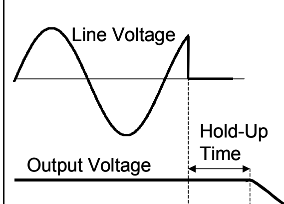
As it can be seen in Fig.1, each conversion block will provide a different output voltage, and some combinations are possible. Therefore the storage capacitor can operate with different voltages. The main goal of this paper is to identify which is the best option from the point of view of the size and cost of the storage capacitor. To comply with this aim it will be developed a comparison of the storage capacitor size which is obtained among the different options which appear to develop the AC/DC power supply. These options will consider two basic structures, the power chains shown in Fig. 1 and Fig.2, and the different voltages which can be selected for nodes A and B. Furthermore, a revision of the key factors which determine the size and cost of the storage capacitor have been analyzed.

II. STORED ENERGY AND MINIMUM CAPACITANCE VALUE.

In power supplies, two are the main situations which require energy to be stored in electrolytic capacitors. These are shown in Table I together with the minimum needed capacitance value (C_{MIN}).

- In any AC/DC converter it is required to store energy in order to balance the input and output power waveforms (see Table .I.a). In this case, the C_{MIN} value, necessary to limit the storage-capacitor voltage ripple (100 – 120 Hz ripple), is given by (1). Where: P_O is the full load output power (see Fig.1), V_O is the output voltage of the AC/DC front-end, V_{PP} is the required storage capacitor voltage ripple, η is the whole efficiency of DC/DC blocks, and f_{LINE} is the line frequency.
- In addition, in AC/DC converters used to feed computer related applications and telecommunication applications, a hold-up time capability must be provided. The needed capacitance to deliver the output power during the hold-up time is determined by means of (2). Where: P_O is the full load output power, HUT is the hold-up time specification, η is the efficiency of the "discharge converter" (this converter takes the energy from the storage capacitor to feed the load during the hold-up time). V_C is the nominal voltage on the storage capacitor and V_F is the voltage on the storage capacitor when the "discharge converter" goes out of regulation.

TABLE I. ENERGY STORAGE IN POWER SUPPLIES AND THE MINIMUM REQUIRED CAPACITANCE VALUE.

 **a)**	$C_{MIN} = \dfrac{\dfrac{P_O}{\eta}}{2\cdot\pi\cdot f_{LINE}\cdot V_{PP}\cdot V_O}$ (1)
 **b)**	$C_{MIN} = \dfrac{2\cdot Energy}{V_C^{2} - V_F^{2}} = \dfrac{2\cdot\dfrac{P_O}{\eta}\cdot HUT}{V_C^{2} - V_F^{2}}$ (2)

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III. POWER CHAIN CONFIGURATIONS

If we consider to feed a microprocessor or DSP from the AC line voltage, the power supply could present two different configurations which are shown in Fig.1 and Fig. 2.

- *Two stage - approach*. The power chain shown in Fig.1 is based on a two - stage AC/DC converter. Therefore two inner nodes with two different voltages appear. These are the output nodes of the AC/DC block and the DC/DC block. In order to reduce the line frequency voltage ripple at node A, it is always necessary to store energy in a storage capacitor placed at this node. This capacitor can also be use to provide the hold-up time capability. However, another option is to store a portion of the total energy at node B. One of the aims of this paper is to determine the best voltage on node A and also, if it is feasible, how to distribute the energy between nodes A and B.

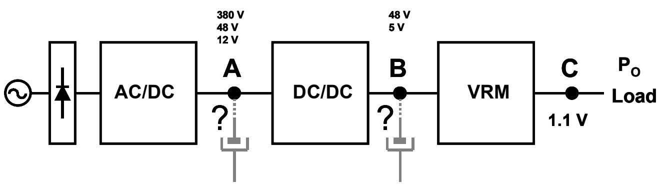

Figure 1. Structure based on a two – stage AC/DC converter.

- *Single stage approach*. Other possible configuration is shown in Fig. 2. This solution is based in a single-stage AC/DC converter. The approach shown on Fig.2 could seem a interesting solution due to the number of conversion steps. However, a low efficiency of the AC/DC converter, and / or a high size and cost of the storage-capacitor could reduce the interest of this approach. Also in this configuration, the capacitor C_1 must have a value wide enough, in order to reduce the line frequency ripple on the voltage V_{C1}. Specially in this case, it is important to determine, if the energy can be distributed between the capacitor C_1 and a second capacitor placed at node A.

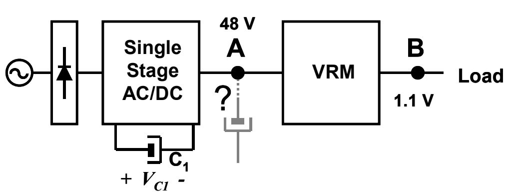

Figure 2. Structure based on a single – stage AC/DC converters.

IV. BEST VOLTAGE TO STORE THE ENERGY

As it can be seen in Fig.1, it is possible to select different voltage values for the nodes A and B. These voltages require to select the suitable topology, some possibilities are the following:

- Boost PFC front-end (see [1]) plus a 5 to 1.1V VRM. This solution requires a 400 to 5V DC/DC converter.
- Boost PFC front-end plus 48 to 1.1V VRM (see [2]). This solution requires a 400 to 48V DC/DC converter.
- Flyback PFC front-end (see [3]) plus 5 to 1.1V VRM. A 48 to 5V DC/DC converter is required.

In order to determine which is the best option according to the size of the storage capacitor, it have been developed the Table II and the Table III:

- In Table II the size of the storage capacitor is compare for a voltage at node A of 380V, 48V and 12 V, and three different hold-up time values (HUT), the output power is 100W. The data of this table have been obtained according to (2). In (2), the term V_F depends on the regulation capability of the discharge converter. In order to compare different converters with an unknown regulation capability (it depends on the topology and design of the converter), the V_F term has not been taking into account. In [4] can be found a detailed revision of the influence of the topology and the design of the converter on V_F.
- In Table III the size of the storage capacitor is compare for 380 and 48 V at node A and three different values of the voltage ripple on the storage capacitor. The data of this table have been obtained according to (1).

TABLE II. SIZE OF THE STORAGE CAPACITOR FOR THREE DIFFERENT HOLD-UP TIME VALUES (HUT).

Po = 100W	**V_A = 380 V**					
HUT (ms)	***C_{MIN} (µF)***	***$V_{PP}/2$ (V)***	***V_{RATED} (V)***	***Capacitor***	***Dimensions Diam. x lenght (mm x mm)***	***Volume (cm^3)***
10	14.7	30	450	1 x 22µF / 450 V	16 x 31.5	6.33
15	25.7	21	150	1 x 33µF / 450 V	16 x 25	5.03
20	34.2	15	400	1 x 47µF / 400 V	16 x 31.5	6.33
Po = 100W	**V_A = 48 V**					
10	1070	3.82	63	4 x 330µF / 63 V	10 x 20	6.28
15	1610	2.54	63	5 x 330µF / 63 V	16 x 25	7.85
20	2143	1.91	50	1 x 2200 µF / 50 V	16 x 31.5	6.33
Po = 100W	**V_A = 12 V**					
10	17	0.773	16	2 x 6800 µF / 16 V	16 x 31.5	12.67
15	26	0.516	16	3 x 10000 µF / 16 V	18 x 35.5	27.1
20	34	0.387	16	4 x 10000 µF / 16 V	18 x 35.5	36.1

The volume data shown in Table III and Table II corresponds to the commercial series of electrolytic capacitors Panasonic M, see [5]. Although more than 20 commercial series of electrolytic capacitor have been investigated among different manufacturers and different technologies (general purpose, low impedance, wide temperature range, axial and radial types…), in all of these series, the conclusions have been identical. Due to the space constraint, just a few of these series will be used to describe the more significant aspects.

TABLE III. SIZE OF THE STORAGE CAPACITOR FOR THREE DIFFERENT VALUES OF THE VOLTAGE RIPPLE ON THE STORAGE CAPACITOR (V_{PP})

Po = 100W	**V_A = 380 V**					
V_{PP} (%)	***C_{MIN} (µF)***	***$V_{PP}/2$ (V)***	***V_{RATED} (V)***	***Capacitor***	***Dimensions Diam. x lenght (mm x mm)***	***Volume (cm^3)***
10	27.21	19	400	1 x 33µF / 400 V	16 x 25	5.03
15	18.14	28.5	450	1 x 22µF / 450 V	16 x 25	5.03
20	13.61	38	450	1 x 22µF / 450 V	16 x 25	5.03
Po = 100W	**V_A = 48 V**					
10	1700	2.4	63	1 x 2200 µF / 63 V	18 x 35.5	9.033
15	1137	3.6	63	4 x 330µF / 63 V	10 x 20	6.28
20	690	4.8	63	1 x 1000 µF / 63 V	16 x 25	5.03

The main aspects that can be highlighted taking into account Table II an Table III are the following:

- To store the energy, selecting a voltage on the storage capacitor of 380V and 48 V placed at node A, requires a very similar volume (the same conclusion can be obtained taking into account both, the HUT in table II and the voltage ripple in table III). In the same conditions, the size for a voltage of 12 V is much higher.

  This fact can be described as follows. Although more micro Farads must be used at low voltage to store the same quantity of energy (see Fig.3.a), low voltage capacitors presents a lower size (see Fig.3.b). The combination of these trends provides the actual relationship between the volume of the capacitor and the voltage value in which the energy is stored, (see Fig.3.c).

  Taking these trends into account, it can be concluded that **above a nominal voltage around 35 - 50 V, there is not a value which drastically reduces the size of the storage capacitor**.

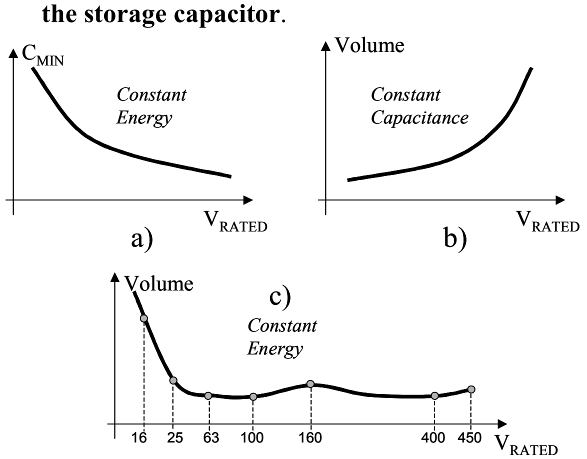

Figure 3. Actual trend of the storage capacitor size with the voltage.

- For V_A = 48 V and a HUT = 10 ms is required a capacitance value C_{MIN} = 1070 µF. A possible actual capacitor could be 2 x 1000 µF, but its exploitation is too low. Another possibility is 4 x 330 µF, now the exploitation is slightly better, but 4 capacitors are used and the size increases in relation to a single capacitor. The closer is the required value to the commercial values, the higher the exploitation is and the smaller size is obtained. This aspect is applicable to capacitance and rated voltage and can be observed in quite a lot of cases in Table II and Table III. Therefore, it can be conclude that **the exploitation of the commercial values of the capacitance and the rated voltage has a important influence on the size of the storage capacitor**.

V. INFLUENCE OF THE VOLTAGE SWING ON THE STORAGE CAPACITOR SIZE

In a two-stages approach, the storage-capacitor voltage is regulated by means of the control loop of the PFC front-end. However in single-stage converters this voltage is not regulated and it could varies with the line voltage and also with the load. Therefore (2) must be adapted in order to take into account the voltage swing. (3) is the rewritten equation if V_F is not considered.

The voltage on storage capacitor at low line ($V_{C@Low\ line}$) will determine the minimum value of the capacitance to comply with the required energy. On the other hand, the voltage at high line will impose the rated voltage of the capacitor. Therefore, if the line variation is transferred to the storage capacitor voltage (and even increased if this voltage is load dependent), it will required both, high capacitance and high rated voltage, so the size of the capacitor will seriously penalized.

$$C_{MIN} = \frac{2 \cdot \frac{P_{O\_FL}}{\eta_{Disch}} \cdot HUT}{(V_{C\,@\,Low\,line})^2} \qquad (3)$$

Expression (3) has been applied to four different AC/DC converters and the obtained results have been presented in Fig.4. These results show how each one of the proposed solutions gets a different nominal voltage and voltage swing on the storage capacitor. The results shown in Fig.4 have been obtained using the Panasonic M Series of electrolytic capacitors [5]. The first alternative analyzed is a two-stage approach with Boost PFC front-end [1]. The rest of converters studied are single-stage PFC AC/DC converters which have been classified into three different groups. Note that these groups are not referred to a concrete topology, but each group obtains similar results concerning the storage-capacitor voltage.

The storage-capacitor voltage results to be line and load dependant into the first group of single-stage converters, [6], [7]. The second group obtains a voltage on storage capacitor clamped to the peak value of line voltage, [8], [9]. Finally, the last family of converters to compare with present both, a low voltage range as well as a low voltage swing on its storage-capacitor. Two possible converters have been proposed in [10] and [11].

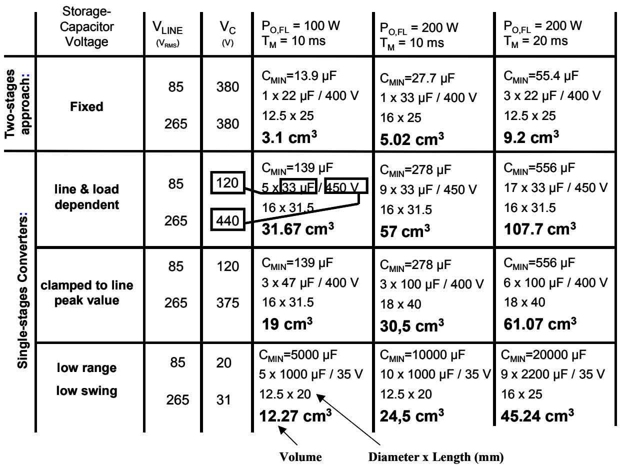

Figure 4. Storage capacitor size comparison in four AC/DC converters.

In Fig.4 it is shown, how the best results correspond to the two-stages approach due to the fixed storage capacitor voltage. Between the three single-stage solutions analyzed, the converter proposed in [10]-[11] present a lower volume for the storage capacitor for the three different energies (P_O x HUT) considered. The reduced voltage swing of V_C in this solution reduces the size in spite of the low voltage reached, 20 ÷ 31 V.

As conclusion, **if the voltage swing is produced, this is, perhaps, the factor with the stronger influence on the size of the storage capacitor**.

VI. DISTRIBUTION OF THE ENERGY AMONG THE DIFERENT NODES OF TH POWER CHAIN

To provide a hold –up time of 20 ms to a load of 100W, it is required to store an energy of 2.47J for a "discharge power chain" presenting an efficiency of 90% x 90% (2J/(0.9 x 0,9)). In Fig. 5, a two-stages structure is considered, with V_A=380 V and V_B = 48 V. In order to limit the line-frequency ripple at node A below a 20%, a minimum capacitance of 13.61 µF / 450 V is required (see Table III). The upper commercial value is 22 µF / 450V which will store an energy of 1.58 J. Two options are possible to store the required energy:

- *Option 1*: To store, at node A, all the energy required to provide the hold-up time specification. This energy is supposed to be higher than the required energy to limit the line frequency ripple. The obtained results are shown in Table IV.
- *Option 2*: To store, at node A, just the energy required to limit the line frequency ripple. The rest of the energy to provide the hold-up time will be store at node B. As it can be seen also in Table IV, in the case of a two-stages structure, this option is not too much interesting, unless the exploitation of the capacitor allows reducing the total size.

TABLE IV. ENERGY DISTRIBUTION AND SIZE OF THE REQUIRED STORAGE CAPACITOR

	Energy Node A (J)	Energy Node B (J)	Capacitor		Total Volume (cm^3)
			Node A	*Node B*	
OPTION 1	2.47	0	1 x 47 µF / 400 V	-------	6.33
OPTION 2	1.58	0.8	1 x 22µF / 400 V	1 x 1000 µF / 50 V	8.1

However if the structure is based on a single-stage approach, since the storage-capacitor size of the AC/DC converter is penalized due to the voltage swing, the distribution of the storage capacitor should be an interesting option to reduce its total size. In the storage capacitor of the AC/DC converter should be store just the needed energy to reduce the voltage ripple and the rest of the required energy to provide the hold-up time should be stored at node A (See Fig 2).

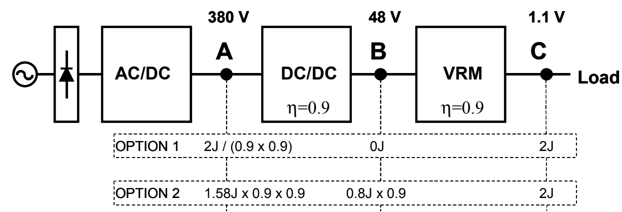

Figure 5. Possible energy distribution between nodes A and B

VII. MANUFACTURING FACTORS ON STORAGE CAPACITOR SIZE - COST

In section IV, the concept of capacitor exploitation has been introduced. This concept is closely related with the fact that commercial capacitors present capacitance values and rated voltage values that vary in discrete steps, not in a continuous way. Therefore, the closer the design values to the commercial values are, the lower the size of the storage capacitor is. Now, two questions arise: Within a commercial series of electrolytic capacitor, is there any capacitor which size is better exploited in relation with the maximum energy that can be stored in it? and which factor has a mayor influence on electrolytic capacitor cost?

In order to answer these questions, several commercial series of electrolytic capacitors have been analyzed: In Table V, an excerpt of the Panasonic M Series of electrolytic capacitors datasheets [5] is shown. Moreover, in this table, it has been added some new parameters:

- The volume of the capacitor (cm^3).
- The maximum energy, which can be stored in each capacitor. This energy has been expressed in Joules (J)

$$E = \frac{1}{2} \cdot C \cdot V_{RATED}{}^2 \tag{4}$$

- The energy-volume ratio expressed in Joules/liter (J/l):

$$EVR = \frac{\frac{1}{2} \cdot C \cdot V_{RATED}{}^2}{Volume} \tag{5}$$

- The cost of each capacitor has been obtained from Mouser Electronic (electronic components distributor) [11].

We emphasize that the cost of an electronic component is quite variable and it depends on a lot of different factors. In many cases, commercial aspects have stronger influence than manufacturing aspects. However, it is interesting to study which manufacturing factors settle the prize of the capacitor in order to reduce the cost by means of a right design.

A. *Energy – volume relationship.*

In Fig.6, volume against energy has been plotted. In order to draw this plot, all capacitors data of Table V have been used, moreover, these data have been arranged by increasing energy and they have been presented in the "Volume vs Energy" column. In Fig.7 the same relationship has been plotted, however, the data have been separated to plot some traces corresponding to different rated-voltage values.

As it can be seen in Fig.6, **volume increases linearly with the stored energy** (this relationship can be considered as quite linear, because most of data are close to its linear regression trace), the same conclusion can be obtained from Fig.7. However, in Fig.6, there are some particular data points rising from the linear regression line. These points seem to draw a horizontal line because all of them present the same volume value (9.034 cm^3, 6.33 cm^3, 5.27 cm^3 …). This is due to the fact that the number of available case size in commercial electrolytic capacitor series is quite low.

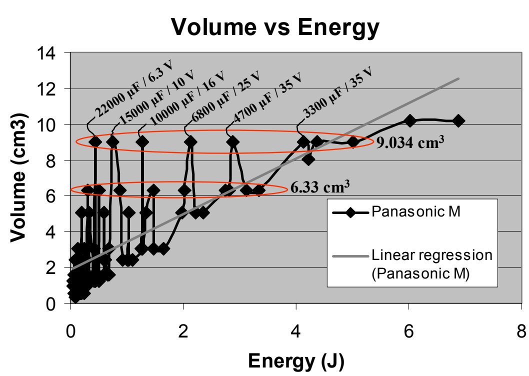

Figure 6. Volume vs Energy. All data of the corresponding column of Table V have been considered.

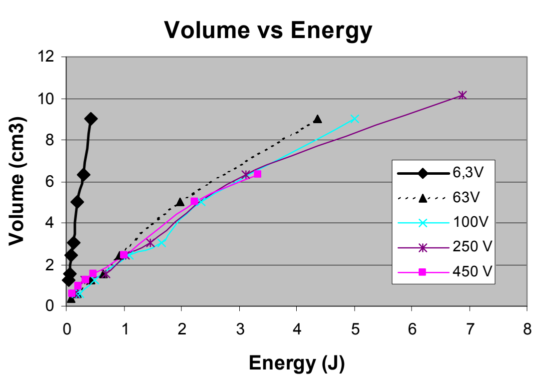

Figure 7. Volume vs energy. In this plot, data have been separated in traces corresponding to different rated voltage values.

Different combinations of capacitance and rated voltage are sold under the same case size. This aspect can be also seen in Fig. 8. In this plot, data points seem to be confined into columns, each one of these columns corresponds to a normalized case size.

An important aspect, which can be observed in Fig.6, is that there are some capacitors presenting a poor energy-volume optimization. Some of these capacitors have been pointed in Fig.6 (22000 µF / 6.3 V…) and they correspond to the extreme values inside a group with the same rated voltage (see Table V). The second horizontal line (6.33 cm^3) is composed for those capacitors placed in the second last position of the group. For a given volume, a capacitor placed close to the linear regression line or place on the right from this line, will present a better energy volume optimization (for a given volume they are able to store a higher energy). As conclusion, capacitors presenting the extreme values of capacitance within each rated-voltage group could be poor optimize and normally its size will be higher.

Lets consider now if some of the groups of electrolytic capacitor presenting the same rated-voltage are poor optimized than others. Taking into account the plots shown in Fig. 7, it can be seen how 6.3V capacitors present a very high volume for a given energy. However, in case of 63V to 450V capacitors, the difference is not so significant. This fact is coherent with the idea shown in Fig.3.c: above 35 - 50 V, there is not a value that drastically reduces the size of the storage capacitor.

B. *Key factors on capacitors cost.*

If the data of Table V are observed, it can be concluded that the cost of the electrolytic capacitors are not related to the capacitance value or to the rated-voltage value.

In the column "Cost vs Volume" of Table V, the data of all the Panasonic M Series capacitors have been arranged by increasing volume. In Fig.8 these data have been plotted and it can be seen how **the cost of the electrolytic capacitors increases linearly with the volume**. The same conclusion can be obtained from Fig. 9, in which data have been separated to plot some traces corresponding to different rated voltages.

In Fig.10 it has been drawn the cost-energy relationship for several rated-voltage values. It can be seen, how the cost of the electrolytic capacitors increases linearly with the stored energy. However it is important to notice that the slope of the 6.3V trace is really high in comparison to the slope of 63V…450V traces (among these traces there are just small differences). The plots in Fig.10 are closely related to the plots of Fig.7 and consequently the conclusions about size and cost are quite similar.

In Fig.11, it is represented the cost of the capacitor against its energy-volume ratio (ERV) for some rated voltage values. This plot provide information about which is the cost of the energy-volume optimization of the capacitor. Taking into account Fig.11, some important aspects can be highlighted:

TABLE V. EXCERPT OF THE PANASONIC M SERIES ELECTROLYTIC CAPACITORS DATASHEETS [5]

Cap. (uF)	Rated Voltage (V)	Diameter (mm)	Length (mm)	Volume (cm3)	Energy (J)	Energy-volume ratio (J/litre)	Cost (€)	Cost vs Volume		Volume vs Energy	
								Volume	Cost	Energy	Volume
2200	6,3	10	16	1,257	0,0437	34,74	0,66	0,349	0,37	0,0437	1,257
3300	6,3	10	20	1,571	0,0655	41,69	0,81	0,578	0,41	0,0500	0,982
4700	6,3	12,5	20	2,454	0,0933	38,00	1,13	0,578	0,41	0,0602	0,578
6800	6,3	12,5	25	3,068	0,1349	43,99	1,42	0,578	0,41	0,0655	1,571
10000	6,3	16	25	5,027	0,1985	39,48	2,03	0,578	0,41	0,0933	2,454
15000	6,3	16	31,5	6,333	0,2977	47,00	2,54	0,578	0,43	0,0933	0,349
22000	6,3	18	35,5	9,034	0,4366	48,33	3,64	0,578	0,49	0,1013	0,578
1000	10	10	12,5	0,982	0,0500	50,93	0,52	0,578	0,5	0,1031	0,578
2200	10	10	20	1,571	0,1100	70,03	0,76	0,578	0,59	0,1100	1,571
3300	10	12,5	20	2,454	0,1650	67,23	1,08	0,578	0,62	0,1250	0,578
4700	10	12,5	25	3,068	0,2350	76,60	1,34	0,982	0,52	0,1280	1,257
6800	10	16	25	5,027	0,3400	67,64	1,88	0,982	0,55	0,1348	0,578
10000	10	16	31,5	6,333	0,5000	78,95	2,27	0,982	0,55	0,1349	3,068
15000	10	18	35,5	9,034	0,7500	83,02	3,5	0,982	0,55	0,1469	0,982
470	16	8	11,5	0,578	0,0602	104,07	0,41	0,982	0,69	0,1469	0,578
1000	16	10	16	1,257	0,1280	101,86	0,65	1,257	0,66	0,1650	2,454
2200	16	12,5	20	2,454	0,2816	114,73	1,13	1,257	0,65	0,1650	0,578
3300	16	12,5	25	3,068	0,4224	137,68	1,45	1,257	0,68	0,1985	5,027
4700	16	16	25	5,027	0,6016	119,68	1,98	1,257	0,67	0,1985	0,578
6800	16	16	31,5	6,333	0,8704	137,43	2,32	1,257	0,65	0,2021	0,982
10000	16	18	35,5	9,034	1,2800	141,69	3,46	1,257	0,8	0,2228	0,982
330	25	8	11,5	0,578	0,1031	178,40	0,41	1,257	0,72	0,2350	3,068
470	25	10	12,5	0,982	0,1469	149,61	0,55	1,257	0,71	0,2350	0,578
1000	25	10	20	1,571	0,3125	198,94	0,8	1,257	0,83	0,2750	0,982
2200	25	12,5	25	3,068	0,6875	224,09	1,38	1,571	0,81	0,2816	2,454
3300	25	16	25	5,027	1,0313	205,16	1,95	1,571	0,76	0,2816	1,257
4700	25	16	31,5	6,333	1,4688	231,90	2,46	1,571	0,8	0,2879	1,257
6800	25	18	35,5	9,034	2,1250	235,23	3,62	1,571	0,86	0,2977	6,333
220	35	8	11,5	0,578	0,1348	233,11	0,41	1,571	0,86	0,3125	1,571
330	35	10	12,5	0,982	0,2021	205,88	0,55	1,571	1,03	0,3125	1,257
470	35	10	16	1,257	0,2879	229,08	0,68	1,571	1,14	0,3341	1,257
1000	35	12,5	20	2,454	0,6125	249,55	1,25	1,571	1,19	0,3400	5,027
2200	35	16	25	5,027	1,3475	268,08	2,05	2,454	1,13	0,4125	1,257
3300	35	16	31,5	6,333	2,0213	319,14	2,51	2,454	1,08	0,4224	3,068
4700	35	18	35,5	9,034	2,8788	318,67	3,76	2,454	1,13	0,4224	1,571
100	50	8	11,5	0,578	0,1250	216,24	0,41	2,454	1,25	0,4366	9,034
220	50	10	12,5	0,982	0,2750	280,11	0,55	2,454	1,22	0,4366	1,257
330	50	10	16	1,257	0,4125	328,26	0,67	2,454	1,35	0,4759	1,571
470	50	10	20	1,571	0,5875	374,01	0,86	2,454	1,34	0,5000	6,333
1000	50	12,5	25	3,068	1,2500	407,44	1,52	2,454	1,39	0,5000	1,257
2200	50	16	31,5	6,333	2,7500	434,20	2,51	2,454	1,62	0,5875	1,571
3300	50	18	35,5	9,034	4,1250	456,63	3,96	3,068	1,42	0,6016	5,027
47	63	6,3	11,2	0,349	0,0933	267,15	0,37	3,068	1,34	0,6016	2,454
100	63	8	11,5	0,578	0,1985	343,31	0,43	3,068	1,45	0,6125	2,454
220	63	10	16	1,257	0,4366	347,43	0,65	3,068	1,38	0,6549	1,571
330	63	10	20	1,571	0,6549	416,91	0,86	3,068	1,52	0,6875	3,068
470	63	12,5	20	2,454	0,9327	380,02	1,22	3,068	1,85	0,6875	1,571
1000	63	16	25	5,027	1,9845	394,80	2,26	3,068	2	0,7500	9,034
2200	63	18	35,5	9,034	4,3659	483,29	3,94	3,068	2,01	0,8704	6,333
33	100	8	11,5	0,578	0,1650	285,44	0,49	5,027	2,03	0,9327	2,454
47	100	8	11,5	0,578	0,2350	406,54	0,5	5,027	1,88	1,0125	2,454
100	100	10	16	1,257	0,5000	397,89	0,8	5,027	1,98	1,0313	5,027
220	100	12,5	20	2,454	1,1000	448,18	1,35	5,027	1,95	1,0313	2,454
330	100	12,5	25	3,068	1,6500	537,82	1,85	5,027	2,05	1,1000	2,454
470	100	16	25	5,027	2,3500	467,52	2,41	5,027	2,26	1,2500	3,068
1000	100	18	35,5	9,034	5,0000	553,48	4,56	5,027	2,41	1,2800	9,034
22	160	10	16	1,257	0,2816	224,09	0,72	5,027	2,19	1,2800	3,068
33	160	10	20	1,571	0,4224	268,91	1,03	6,333	2,54	1,3475	5,027
47	160	12,5	20	2,454	0,6016	245,11	1,34	6,333	2,27	1,4688	6,333
100	160	12,5	25	3,068	1,2800	417,21	2	6,333	2,32	1,4688	3,068
220	160	16	31,5	6,333	2,8160	444,62	2,92	6,333	2,46	1,6500	3,068
330	160	18	31,5	8,016	4,2240	526,96	4,07	6,333	2,51	1,9845	5,027
470	160	18	40	10,179	6,0160	591,03	5,24	6,333	2,51	2,0213	6,333
4,7	250	8	11,5	0,578	0,1469	254,09	0,59	6,333	2,92	2,1250	9,034
10	250	10	16	1,257	0,3125	248,68	0,71	6,333	3,01	2,2275	5,027
22	250	10	20	1,571	0,6875	437,68	1,14	6,333	2,95	2,3500	5,027
33	250	12,5	20	2,454	1,0313	420,17	1,39	8,016	4,07	2,7500	6,333
47	250	12,5	25	3,068	1,4688	478,74	2,01	9,034	3,64	2,8160	6,333
100	250	16	31,5	6,333	3,1250	493,41	3,01	9,034	3,5	2,8788	9,034
220	250	18	40	10,179	6,8750	675,42	5,26	9,034	3,46	3,1250	6,333
1	450	8	11,5	0,578	0,1013	175,16	0,62	9,034	3,62	3,3413	6,333
2,2	450	10	12,5	0,982	0,2228	226,89	0,69	9,034	3,76	4,1250	9,034
3,3	450	10	16	1,257	0,3341	265,89	0,83	9,034	3,96	4,2240	8,016
4,7	450	10	20	1,571	0,4759	302,95	1,19	9,034	3,94	4,3659	9,034
10	450	12,5	20	2,454	1,0125	412,53	1,62	9,034	4,56	5,0000	9,034
22	450	16	25	5,027	2,2275	443,15	2,19	10,179	5,24	6,0160	10,179
33	450	16	31,5	6,333	3,3413	527,55	2,95	10,179	5,26	6,8750	10,179

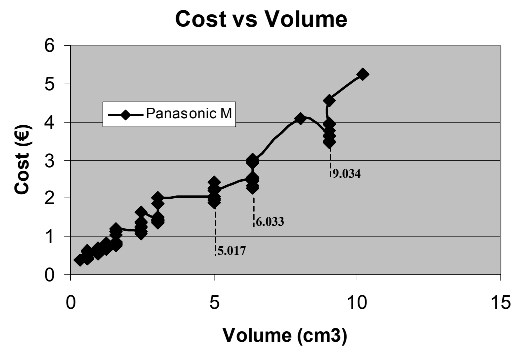

Figure 8. Cost vs Volume. All capacitor data of Table V have been considered.

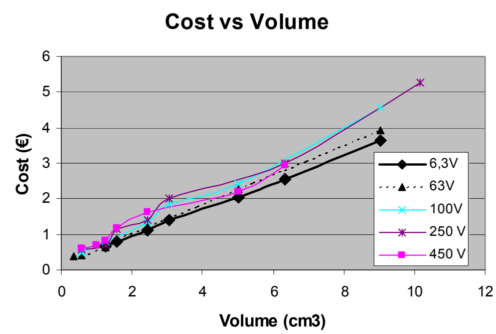

Figure 9. Cost vs Volume. For several values of the rated-voltage.

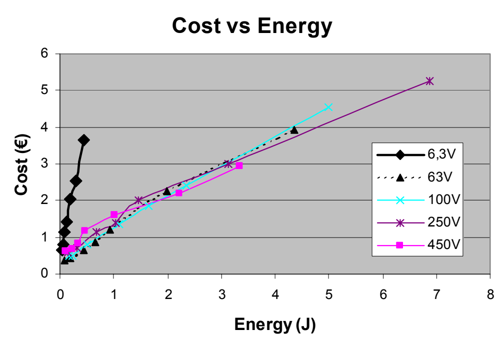

Figure 10. Cost vs Energy. For several values of the rated-voltage.

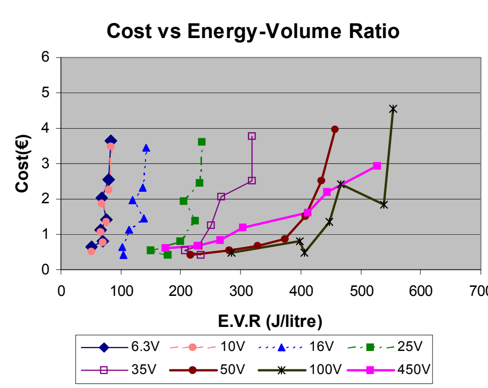

Figure 11. Cost vs Energy-Volume Ratio. For several values of the rated-voltage.

- For each rated-voltage value, **the cost of the capacitor increases with the energy-volume ratio**. The traces corresponding to low rated-voltage capacitors (6.3V..25V) presents a high slope, therefore, storing energy with this type of capacitors is usually expensive because they are not well optimized.

- If the traces corresponding to 50V and 450V are considered, it can be seen that, up to 400 J/l, it is cheaper to use 50V capacitors. However, for higher EVR values, it is cheaper to use 450V capacitors. On the other hand, the 100V trace in Fig. 11 is below the 450V trace for most of data points. As conclusion, for the same level of energy-volume optimization (same EVR), it is cheaper to use 100V capacitors than 450V, up to 550 J/l.

  A possible way to explain this fact could be the following: For a given energy-volume optimization, if the use of the particular capacitor is very common, its sales volume will be high enough and consequently electronic-components distributors could reduce the prize of this capacitor. However if the particular capacitor which achieve this given ERV value (for this rated-voltage) is not enough common, its cost could increases.

As conclusion, 50V, 63V, 100V and 450V capacitors present a similar energy-volume optimization, therefore, the required storage capacitor will present a similar size and cost if the energy is stored at 50V or at 450V. This fact is also coherent with the idea shown in Fig.3.a.

VIII. CONCLUSIONS

A complete discussion about the key factors to determine the size and cost of the storage capacitor in AC/DC power supplies has been presented in this paper. The most significant aspects are the following:

- Above a nominal voltage around 35, there is not a value that drastically reduces the size of the storage capacitor. It can be used voltages of 50, 63, 100…450V with very similar results.

- The exploitation factor has an important influence on the size of the storage capacitor. The closer the design values to the commercial ones are, the lower the size of the storage capacitor. To look for common-use capacitors could be a good practice in order to reduce the capacitor cost.

- The voltage swing on the storage-capacitor voltage is a decisive aspect to reduce the size and cost of this capacitor in single-stage AC/DC converters. The higher the voltage swing, the higher the size and cost.

- The distribution of the energy is an interesting option, mainly in case of a structure base on a single-stage AC/DC converter.

- The volume of the capacitor increases linearly with the maximum energy which can be stored in it. The cost is closely related with the size of the capacitor and increases as well with the energy-volume ratio.

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