SELECTION CRITERIAS FOR SINGLE-CONVERTER VOLTAGE SAG AND OUTAGE COMPENSATOR

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INTRODUCTION

The purpose of this work is to define a methodology that allows to select the most suitable topology for a single-converter based Voltage Sag and Outage Compensator (VSOC). In most of the research studies the selection of the compensation topology is not treated, and if it is, it is only based on the power rating of the converter. But the evaluation of a suitable topology should consider all the components such as the electromagnetic elements, energy storage devices, static switches, filters and others. Single-conversion topologies (SCT) improve the efficiency, reliability and maintenance cost of the well-known double-conversion based UPS systems. Three of these single-conversion VSOC are analysed: the Line Interactive Transformer Compensator (LITC), the Line Interactive Reactance Compensator (LIRC) and the Line Interactive Switch Compensator (LISC). In order to study the optimal sizing of the elements of each topology the design task consider a 1.6 MVA (0.8 Power Factor) load. The design task must be followed by a comparison step, which is carried out by a new evaluation tool. This methodology is an adaptation of the evaluation work presented in [1] and it is based on the computation of the so-called "coefficients of use". Each family of elements (semiconductors, inductances and capacitors) has its own coefficient. These coefficients show the ratio between the power of each family of elements and the overall power of the protected load. Thanks to these coefficients, the best-suited topology (per each application) can be identified and several "improvement opportunities" are easily localized. Adding appropriate cost coefficients, overall cost can be computed.

SINGLE-CONVERTER VOLTAGE SAG AND OUTAGE COMPENSATOR TOPOLOGIES

In order to protect critical loads from voltage sags and outages most of the customers have installed Uninterrupted Power Supply (UPS) systems. Chemical-type batteries are commonly used for energy storage purposes in most UPS devices wich are based on double-conversion topologies, so high protection level is guaranteed. But due to high maintenance costs, large space requirements and poor efficiency, these UPS solutions are not suitable for powers above 750Kw. So it is interesting to look for new topologies as the power electronics-based single-conversion compensator (SCC), which seems to be suitable for this purpose. Single-conversion topologies have to guarantee both good protection level and high energetic efficiency. Considering new energy storage systems, as flywheels, space and maintenance-cost reductions can be achieved.

For any industrial (commercial) product development, topology selection based on the desired compensation strategy and optimal rating of the components become critical. Each one of the compensation topologies provides some capabilities with several implications that can be economically evaluated in order to determine the optimal solution [2].

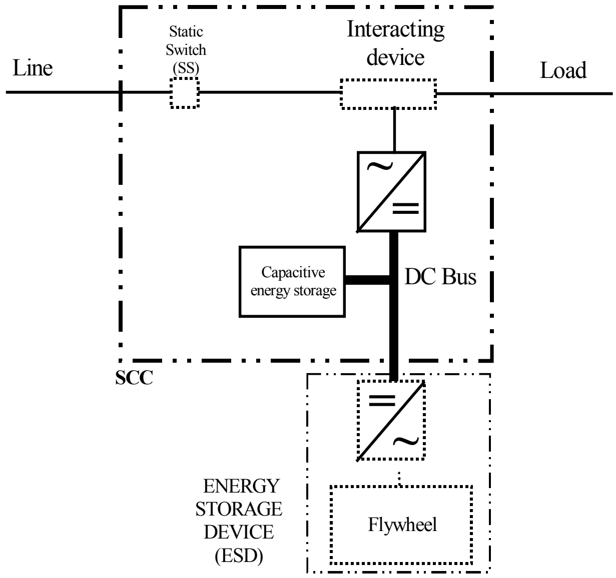

Figure 1: Generic SCT

Power-electronics based SCC devices used in power quality improvement systems fall within two different topology families: the *series* topology family and the *parallel* one. This classification is related to the type of connection between the main compensation converter and the protected load. For LV sag compensation purposes, series topology is mainly used [3-7], whereas the parallel topology is dedicated to outage compensation [1], voltage balancing [8], [9], active filtering and Flicker compensation [10]. Some parallel devices make use of the non-desired line impedance as the active compensation element, as the D-STATCOM of [4] does for MV sag compensation. When large compensation capabilities are desired hybrid structures are commonly used, where both parallel and series topologies are employed in a coordinated way [1],[11-13].
As the above mentioned works are mainly focused in control or design steps, none of them establishes the suitability of one or other topology for any given quality problem. Several studies establish this suitability by the evaluation of the compensation converter rating, but a thorough evaluation must consider other structural differences such as injection transformers, bypass switches, filters and others [14]. The work presented here is in line with this research framework

and tries to provide the selection criteria for single-converter voltage sag and outage compensators.
Due to the large amount of compensator topologies it is important to establish the set of the most suitable ones for a given functional feature. Considering the sag and short outage compensation to be the target tasks, three different configurations have been selected. All of them match with the general diagram of Fig. 1 and are classified according to the type of interaction they have with the line (in dashed lines). The energy storage device (flywheel and inverter) is only necessary if short outage compensation (≈15sec) is required. Nevertheless this element is present at the three proposed topologies and consequently it does not provide any useful data for the selection task. For that reason it is not considered in this work later on.

Line Interactive Reactor Compensator (LIRC)

This topology is based on a series inductance L_S placed between the line and the load (Fig. 2). The converter acts as a current source, which interacts with L_S and generates a series voltage according to the difference between the desired output voltage and the line voltage. This topology is used by [15] in the next working modes: current conditioning mode, voltage restoring mode (compensation of sags, voltage unbalances and voltage harmonics) and UPS mode. The main elements involved in the compensator design and therefore in the cost are:

S1: bypass switch.
S2: input isolation switch.
S3: output isolation switch.
L_S: series inductor
C_D: AC capacitor bank.
Lf: filtering inductance.
Cf: filtering capacitor.
SS: islanding mode static switch.
Inv: compensation inverter.
C_{DC}: DC-bus capacitors

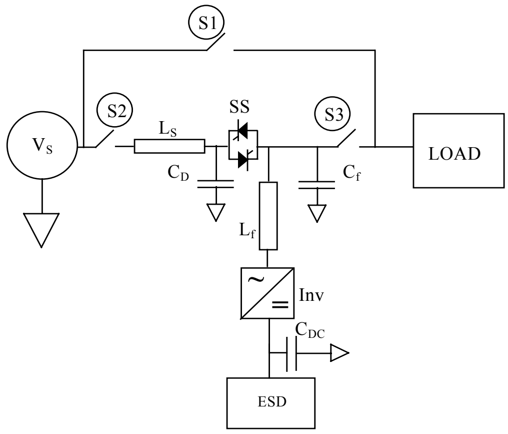

Figure 2: Line Interactive Reactance Compensator (LIRC)

Line interactive switch compensator (LISC)

Without any damping element between the line and the load (Fig. 3), a fast bi-directional switch allows to go to UPS mode at each sag or outage occurrence [16]. With this topology two extra functions can be added: power factor correction and active filtering. The main elements involved in the compensator design are:

S1: bypass switch.
S2: input isolation switch.
S3: output isolation switch.
Lf: filtering inductance.
Cf: filtering capacitor.
SS: islanding mode static switch.
Inv: compensation inverter.
C_{DC}: DC-bus capacitors

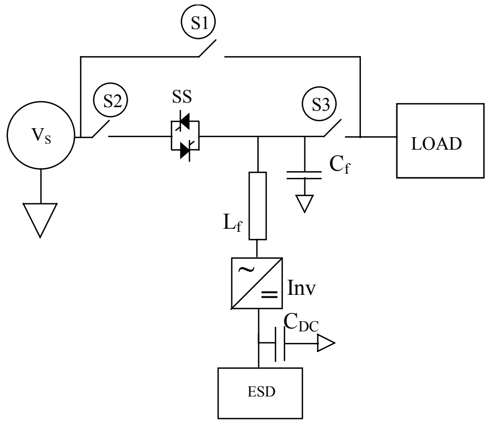

Figure 3: Line Interactive Switch Compensator (LISC)

Line interactive transformer compensator (LITC)

A "voltage injector" transformer is placed in series between the line and the load (Fig. 4). The transformer adds a series voltage according to the difference between the desired output voltage and the line voltage. This injection strategy is studied in [17] but with different static switch configuration and using an extra boost converter. Next elements are used in the LITC:

S1: bypass switch.
S2: input isolation switch.
S3: output isolation switch.
Lf: filtering inductance.
Cf: filtering capacitor.
SS1: islanding mode static switch.
SS2: UPS mode static switch.
Inv: compensation inverter.
C_{DC}: DC-bus capacitors
T_S: Series transformer

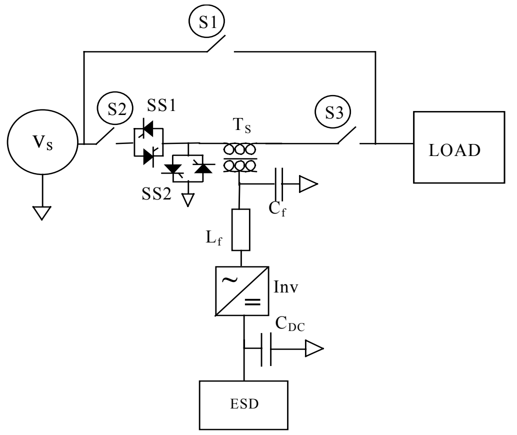

Figure 4: Line Interactive Transformer Compensator (LITC)

EVALUATION METHODOLOGY

In order to be able to compare the presented three topologies, an optimal sizing of the elements must be carried out. But as the sizing of the elements depends on the desired working mode, this has to be defined. Thus five different working modes summarized in TABLE 1 have been selected. "Δt" indicates the duration of the disruption, "event %" refers to the percentage of covered disturbances and "type of injection" indicates if any active power is injected during the compensation task: in the "active" mode the load phase is maintained but the amount of stored energy decreases, whereas in the "reactive" mode the stored energy is kept but the load phase is shifted.

"E" working mode indicates a permanent outage state, which would force the starting of a diesel power system or any similar energy supply device. The SCC has to be able to work in UPS mode during the diesel engine start-up process, which is supposed to last less than 15 sec. "E" mode is the only working mode which requires a flywheel-based additional energy storage device.

TABLE 1- Operating modes

Working Mode	Sag depth	Δt	% events	type of injection
A	20..30%	100ms	55%	ACTIVE
B				REACTIVE
C	50%	300ms	83%	ACTIVE
D				REACTIVE
E	100%	15s	98%	ACTIVE

The protected load is connected at LV level and its rated power is 1,6MVA (Power Factor=0.8).
After the optimal rating of the elements, in order to compare the resulting SCCs, the "coefficients of use" of each family of components are computed. The procedure that allows obtaining the coefficients of use of each family of components is an adaptation of the main idea proposed in [1].

Coefficients of use: Definitions.

The "coefficient of use of a component" defined by [1] is the quotient between the product of the rated *current* and *voltage* of the component and the *apparent injected power*. The problem of this definition is that the injected power during each working mode (except the UPS mode) differs from one topology to other, therefore the same coefficient of use represents different sizing of the components. In order to avoid this problem next definition is proposed and used here: the *coefficient of use of a component* is the quotient between the product of the rated *current* and *voltage* of the component and the *apparent power of the load* S_L. The apparent power of the load S_L is the same for any possible compensation device.

The *coefficient of use of a family of components* is obtained by the addition of the coefficients of use of all the components belonging to the same family. When different criteria is used in the sizing of these components, some equivalence parameters have to be considered in the coefficient of use of each component in order to get an homogeneous set of values. In the same way, if different technologies are involved in the same component family, related cost implications must be considered [18].

The definitions of the coefficients of use of each family of components are listed below.

Coefficient of use of the semiconductors. Depending on the function of each semiconductor device the resulting sizing criteria and the consequent cost coefficient are different:

Inverter switch coefficient:
Used for the switches of the inverter (built with IGBTs in this case), C_{IGBT} is defined as:

$$C_{IGBT} = \frac{\sum_{j=1}^{Ns} V_{IGBTM} I_{IGBTM}}{S_L}$$

Where:

- I_{IGBTM}: maximum current
- V_{IGBTM}: maximum voltage
- N_S: number of commutated devices
- S_L: apparent power of the load

Input static switch coefficient:
Used for input islanding switches (built with thyristors in this case), C_{TH1} is defined as:

$$C_{TH1} = \frac{\sum_{j=1}^{N_S} V_{TH} I_{CC}}{S_L}$$

Where:

- I_{CC}: maximum short-circuit rms current
- V_{TH}: maximum rms voltage

- N_S: number of devices
- S_L: apparent power of the load

Topology management static switch coefficient:
Computed for static switches used for topology management purposes (built with thyristors in this case), C_{TH2} is defined as:

$$C_{TH2} = \frac{\sum_{j=1}^{Ns} V_{TH} I_{TH}}{S_L}$$

Where:

- I_{TH}: maximum rms current
- V_{TH}: maximum rms voltage
- N_S: number of devices
- S_L: apparent power of the load

The semiconductor-family coefficient of use C_{SC} is defined by the addition of the above mentioned coefficients including the normalization constant and the technology-related cost correction factor, if needed.

$$C_{SC}=C_{IGBT}+C_{TH1\_IGBT}+C_{TH2\_IGBT}$$

C_{THi_IGBT} is the coefficient of use of the *i* type thyristor normalized to the IGBT-type cost.

$$C_{THi\_IGBT} = C_{THi} \frac{p_{THi}}{C'_{THi}} \frac{C'_{IGBT}}{p_{IGBT}}$$

Where p_{THi} and p_{IGBT} represent the cost of the components and C'_{THi} and C'_{IGBT} are the coefficient of use of the semiconductors, both based on commercial data-sheets.

Coefficient of use of the electromagnetic components. Called C_L, it is defined as:

$$C_L = \frac{\sum_{j=1}^{N_{L-TR}} S_{L-TRj}}{S_L}$$

Where:

- S_{L-TRj}: 50Hz equivalent power of element *j*
- N_{L-TR}: number of electromagnetic devices
- S_L: apparent power of the load

S_{L-TRj} equivalency is referred to a simple isolation transformer with 50Hz sinusoidal-type currents and working under typical magnetic and thermal conditions. For any given inductor S_{L-TR} is defined as:

$$S_{L-TR} = F_{L-TR} \frac{1}{2} \sum_{j=1}^{Nu} V_{Lj} I_{Lj}$$

Where:

- V_{Lj}: rms nominal voltage
- I_{Lj}: rms nominal current
- N_u: number of coils
- F_{L-TR}: equivalence correction factor

In order to minimize the electromagnetic losses caused by the high commutation frequency, some of the inductors have an air core. This type of inductor requires more turns than those based on ferromagnetic coils so the cost increases. An additional cost of 30% is estimated [1] and so on an equivalence correction factor of $F_{L-TR} = 1.3$ is used.

Coefficient of use of the capacitors. Called C_c, it is defined as:

$$C_C = \frac{\sum_{j=1}^{Nc} S_{Cj}}{S_L}$$

Where:

- S_{cj}: equivalent rated power of capacitor *j*
- N_c: number of capacitors
- S_L: apparent power of the load

Depending on the capacitor type two different power equivalences are needed (for the three studied topologies):

a) *ac capacitors*:

$$Sc = 2\pi 50 C Vc^2$$

where V_c is the capacitor rms voltage

b) *dc capacitors*:

$$Sc = F_C \sum_{j=1}^{N_C} V_C I_C$$

where:

- V_c: capacitor rms voltage
- I_c: capacitor rms current
- F_c: cost correction factor

The cost correction factor F_c takes into account the cost difference between *ac* and *dc* capacitor technologies. An acceptable practical value is F_c=0.25.

Finally, normalized per-unit cost of each component-family has been computed. This value allows to normalize all the involved coefficients in the so-called "global cost-coefficient" C_G and to carry out a global comparative.

$$C_G = C_C \frac{p_C}{C'_C} + C_{SC} \frac{p_{SC}}{C'_{SC}} + C_L \frac{p_L}{C'_L}$$

Where p_C, p_{SC} and p_L represent the cost of the components and C'_C, C'_{SC} and C'_L are the coefficients of use, both based on commercial data-sheets.

COMPARATIVE RESULTS

The coefficients of use of the components considering the LISC topology are shown in TABLE 2. As it can be observed, only three of the proposed five working modes are possible with this compensator. The resulting coefficients indicate that the relative weight of the thyristors in the semiconductor-family is negligible (4.65 against 81.15). TABLE 3 summarizes the global cost-coefficient of each family of components. It is relevant the important value of the capacitor family in the "C" working mode.

TABLE 2- Coefficients of use (LISC)

Mode	C_{DC}	C_{Lf}	C_{Cf}	C_{IGBT}	$C_{TH1\ IGBT}$
A	3.42	2.03	0.057	81.15	4.65
C	10.3	2.03	0.057	81.15	4.65
E	1.44	2.03	0.057	81.15	4.65

TABLE 3- Global cost-coefficients (LISC)

Mode	C_C	C_L	C_{SC}	C_G
A	12.49	8.15	16.2	36.84
C	36.94	8.15	16.2	61.29
E	5.2	8.15	16.2	29.82

The coefficients of use of the components of the LIRC topology are summarized in TABLE 4. This topology covers all the five proposed working modes, but the injected currents (2pu) are the highest within the studied SCCs. This fact leads to higher inductor and semiconductor coefficients. Although smaller C_{DC} is required, an additional AC capacitor bank C_D must be included in order to improve the overall SCC efficiency. Looking at the global-cost coefficient of each family of components, shown in TABLE 5, we can observe that in most of the cases coefficients are several times higher than in the LISC case. The need of some extra inductors and capacitors in this topology decreases the relative weight of the semiconductor-family (only around 25% in the "E" mode).

TABLE 4- Coefficients of use (LIRC)

Mode	C_{DC}	C_{Lf}	C_{Cf}	C_{Ls}	C_D	C_{IGBT}	$C_{TH1\ IGBT}$
A	1.26	4.05	0.3	1.98	1.62	161.82	0
B	1.98	4.05	0.3	2.19	1.71	161.82	0
C	5.16	4.05	0.21	3.24	1.83	161.82	0
D	1.98	4.05	0.21	3.93	1.92	161.82	0
E	0.78	12.3	0.09	6	2.34	161.82	4.65

TABLE 5- Global cost-coefficients (LIRC)

Mode	C_C	C_L	C_{SC}	C_G
A	14.81	24.15	28.8	67.76
B	17.94	25.07	28.8	71.81
C	29.66	29.16	28.8	87.62
D	18.76	31.95	28.8	79.51
E	16.38	73.93	30.6	120.91

TABLE 6 shows the coefficients of use of the components of the LITC topology. There is a new coefficient corresponding to the voltage-injection series transformer, C_T. It can be observed that this coefficient is the main value of the family of electromagnetic components (as C_{Lf} is negligible). All the coefficients are significantly smaller than in the previous cases, leading to smaller global cost-coefficients, as shown in TABLE 7. Note that the extra cost of the transformer is smaller than the overall cost benefit. The reduction of the cost of the capacitors in the "E" working mode observed in all the three SCC topologies is due to the contribution of the extra energy storage system.

TABLE 6- Coefficients of use (LITC)

Mode	C_{DC}	C_{Lf}	C_{Cf}	C_T	C_{IGBT}	$C_{TH1\ IGBT}$	$C_{TH2\ IGBT}$
A	1.23	0.24	0.06	2.04	20.28	0	0
B	0.3	0.57	0.12	4.2	40.56	0	0
C	5.37	0.54	0.06	3.12	40.56	0	0
E	0.87	0.69	0.18	6	50.7	4.65	3

TABLE 7- Global cost-coefficients (LITC)

Mode	C_C	C_L	C_{SC}	C_G
A	4.62	9.36	7.2	21.18
B	1.44	19.15	7.2	27.79
C	19.47	14.6	7.2	41.27
E	3.51	17.4	18	38.92

Fig. 5 summarizes the total cost-coefficients of the three-studied SCCs depending on the working mode.The LIRC topology represents the most expensive solution, but it can be interesting if "D" working mode is required. Otherwise, LITC appears to be the most suitable device for the "A", "B" and "C" working modes. Any SCC designed for "E" type working mode must work in any other mode if a perturbation other than an outage occurs. Although the LISC is slightly cheaper than the LITC in the "E" type working mode, it does not offer the same functional feature set, thus LITC solution becomes the most suitable one.

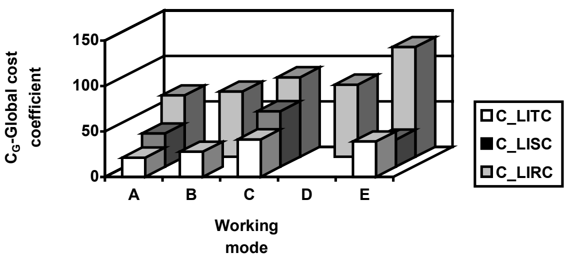

Figure 5: Global cost-coefficients. Comparative

CONCLUSIONS

An adaptation of the evaluation methodology proposed in [1] allows comparing and selecting the optimal single-converter compensator for an actual industrial need: compensation of voltage sags and short outages. Several working modes have been established, thus optimal SCC design can be carried out. These optimised values of the elements are useful in two ways:

- They allow to compare different topologies in terms

of cost-coefficients
- They provide essential input data for the control design problem

Using coefficients of use related to the apparent power of the load and the adequate cost-coefficients, the most suitable topology in terms of cost has been selected: Line Interactive Transformer Compensator, LITC. It has to be noted that this series type compensator is several times cheaper than the parallel type LIRC.
In the case of a MV-SCC, line reactance must be considered, leading to a cost reduction of the LIRC.
In order to complete the selection of the most suitable topology, two important aspects have to be evaluated and compared: time response of the compensator (or dynamic behaviour) and the reliability of the system.

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