Review

Review of Power Conversion and Conditioning Systems for Stationary Electrochemical Storage

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Abstract: This paper deals with the power conversion system architectures to interface a stationary electrochemical storage installation with the network. Theoretical justifications about the conversion system layouts and control, used for actual Italian installations, are given. This paper aims at giving the power energy society an overview of actual possibilities of static conversion of d.c. battery sources.

Keywords: power conversion system; stationary electrochemical storage; batteries; HV network; inverter P/Q control; two-stage converter

1. Introduction

An electrochemical energy stationary storage system (EESSS), as a matter of principle, could be directly connected to the HV network by means of an inverter. Nevertheless, this approach of “direct connection” is not efficient and the chief reason must be attributed to the fact that the EESSS voltage, during the discharge stage, is not constant. For instance, the sodium sulphide (NaS) battery [1–6]
voltage ranges, during discharge, between 100% and 64%, the lithium-ion battery one ranges between 100% and 70%. This behaviour implies two consequences:

- With a direct inverter–EESSS connection, the EESSS (e.g., a battery) voltage variations would imply a remarkable increase of the harmonic content \( h \) in the inverter output voltage. This effect is due to the fact that an inverter generally operates according to a PWM switching scheme [7,8] (see Section 3) in which, in order to pilot the inverter switches, a sinusoidal reference signal is compared with a sawtooth signal with higher frequency. The ratio between the reference signal frequency and the sawtooth one is defined by means of \( m_f \) [8]. The EESSS voltage fluctuations imply the variations of the inverter modulation index \( m_a \) [8], which is the ratio between the reference signal amplitude and the sawtooth one. Consequently, as shown in Table 1, the harmonic content \( h \) of the inverter voltage increases, so penalizing the inverter output quality.

- A \( \Delta u \% \) percentage EESSS voltage variation with respect to the rated value requires the inverter component overrating of \( 1 + \Delta u \% \) as for both the voltage and the current (maximum current corresponding to minimum battery voltage), resulting in an inverter power oversizing of about \( 1 + 2\Delta u \% \). By hypothesizing a current and voltage variation of 20%, the inverter rated power can be inferred by the following simple relation:

\[
P = \Delta V_{\text{max}} \cdot \Delta I_{\text{max}} = V_n(1 + 20\%) \cdot I_n(1 + 20\%) \approx 1.40 P_n = P_n + \Delta P
\]

Hence, it is preferable to connect an EESSS to the electrical network by means of a two-stage converter [9–11] (see Figure 1). It consists of a first stage made by a d.c.-d.c. converter and of a second stage made by a d.c.-a.c. converter so enabling to keep the inverter d.c. side voltage \( U_o \) constant.

**Table 1.** Harmonic content \( h \) as a function of the amplitude modulation \( m_a \) and of the frequency modulation \( m_f \) indexes (greyed rows are absent in three-phase inverters provided \( m_f \) is a multiple of three).

<table>
<thead>
<tr>
<th>( h )</th>
<th>( m_a = )</th>
<th>0.100</th>
<th>0.200</th>
<th>0.300</th>
<th>0.400</th>
<th>0.500</th>
<th>0.600</th>
<th>0.700</th>
<th>0.800</th>
<th>0.900</th>
<th>1.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_f )</td>
<td>( m_f )</td>
<td>1.265</td>
<td>1.242</td>
<td>1.204</td>
<td>1.151</td>
<td>1.084</td>
<td>1.006</td>
<td>0.917</td>
<td>0.818</td>
<td>0.712</td>
<td>0.601</td>
</tr>
<tr>
<td>( m_f \pm 2 )</td>
<td>0.004</td>
<td>0.016</td>
<td>0.035</td>
<td>0.061</td>
<td>0.093</td>
<td>0.131</td>
<td>0.174</td>
<td>0.220</td>
<td>0.268</td>
<td>0.318</td>
<td></td>
</tr>
<tr>
<td>( m_f \pm 4 )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
<td>0.012</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td>( 2m_f )</td>
<td>0.099</td>
<td>0.190</td>
<td>0.268</td>
<td>0.326</td>
<td>0.361</td>
<td>0.370</td>
<td>0.354</td>
<td>0.314</td>
<td>0.255</td>
<td>0.181</td>
<td></td>
</tr>
<tr>
<td>( 2m_f \pm 3 )</td>
<td>–</td>
<td>0.003</td>
<td>0.011</td>
<td>0.024</td>
<td>0.044</td>
<td>0.071</td>
<td>0.103</td>
<td>0.139</td>
<td>0.177</td>
<td>0.212</td>
<td></td>
</tr>
<tr>
<td>( 2m_f \pm 5 )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.001</td>
<td>0.003</td>
<td>0.007</td>
<td>0.013</td>
<td>0.021</td>
<td>0.033</td>
<td></td>
</tr>
<tr>
<td>( 3m_f )</td>
<td>0.401</td>
<td>0.335</td>
<td>0.237</td>
<td>0.123</td>
<td>0.011</td>
<td>0.083</td>
<td>0.146</td>
<td>0.171</td>
<td>0.157</td>
<td>0.113</td>
<td></td>
</tr>
<tr>
<td>( 3m_f \pm 2 )</td>
<td>0.012</td>
<td>0.044</td>
<td>0.089</td>
<td>0.139</td>
<td>0.180</td>
<td>0.203</td>
<td>0.203</td>
<td>0.176</td>
<td>0.127</td>
<td>0.062</td>
<td></td>
</tr>
<tr>
<td>( 3m_f \pm 4 )</td>
<td>–</td>
<td>0.001</td>
<td>0.004</td>
<td>0.012</td>
<td>0.026</td>
<td>0.047</td>
<td>0.074</td>
<td>0.105</td>
<td>0.134</td>
<td>0.158</td>
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</tr>
<tr>
<td>( 4m_f )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.002</td>
<td>0.006</td>
<td>0.017</td>
<td>0.034</td>
<td>0.058</td>
<td>0.084</td>
<td>0.107</td>
<td>0.119</td>
</tr>
<tr>
<td>( 4m_f \pm 3 )</td>
<td>0.002</td>
<td>0.012</td>
<td>0.035</td>
<td>0.070</td>
<td>0.106</td>
<td>0.132</td>
<td>0.137</td>
<td>0.115</td>
<td>0.068</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>( 4m_f \pm 1 )</td>
<td>0.095</td>
<td>0.163</td>
<td>0.185</td>
<td>0.157</td>
<td>0.091</td>
<td>0.008</td>
<td>0.064</td>
<td>0.105</td>
<td>0.105</td>
<td>0.068</td>
<td></td>
</tr>
<tr>
<td>( 4m_f \pm 3 )</td>
<td>0.002</td>
<td>0.012</td>
<td>0.035</td>
<td>0.070</td>
<td>0.106</td>
<td>0.132</td>
<td>0.137</td>
<td>0.114</td>
<td>0.068</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>( 4m_f \pm 5 )</td>
<td>–</td>
<td>–</td>
<td>0.002</td>
<td>0.006</td>
<td>0.017</td>
<td>0.034</td>
<td>0.057</td>
<td>0.082</td>
<td>0.101</td>
<td>0.105</td>
<td></td>
</tr>
</tbody>
</table>
A two-stage converter basically consists in two coupled converters: the first one is a two-quadrant current reversible chopper, carrying out a d.c.-d.c. conversion and consisting of the combination of a step-down (buck) and of a step-up (boost) converter, the second one is a switch-mode d.c.-a.c inverter.

Two possible d.c.-d.c. converter layouts are considered, namely layout 1 and layout 2 of Figure 2. In the following, their behaviour is analysed in EESSS charge and discharge operation in order to identify the more profitable configuration for stationary storage applications.

### Figure 2. Main layouts of the d.c.-d.c. stage of the two-stage converter.
2.1. EESSS Discharge: Layout 1 vs. Layout 2 Behaviour

Let us suppose that an EESSS in discharge mode is connected to a layout 1 d.c.-d.c. converter and that the inductor current \( i_L \) is constantly not null. In this case the d.c.-d.c. converter operates as a step-up (boost) converter and \( T_1 \) conduction is permanently inhibited.

The converter output voltage \( U_o \) can then be expressed [12] as a function of the EESSS voltage \( U_b \) and of the duty cycle \( D \) of the d.c.-d.c. converter (i.e., of \( T_2 \) switch) as:

\[
U_o = \frac{1}{1-D} \cdot U_b
\]

Being \( 0 \leq D \leq 1 \), \( U_o \) is always greater than \( U_b \). This condition enables electric power to flow from the battery to the network. As it is shown in Figure 3b, the battery current \( i_b \) is unidirectional and equal to \( i_L \).

![Diagram showing current and voltage waveforms for Layout 1 discharge operation](image)

Figure 3. Layout 1 discharge operation: current and voltage waveforms (continuous conduction).

If an EESSS is connected, in the same condition above mentioned, to a layout 2 d.c.-d.c. converter (now operating as step-down - buck - converter, being \( T_2 \) inhibited), the output voltage \( U_o \) still depends upon the \( T_1 \) duty cycle \( D \), and it is given by:

\[
U_o = D \cdot U_b
\]

since \( D \) ranges between 0 and 1, \( U_o \) is always lower than \( U_b \). This condition allows the flow of power from the battery to the network but, in this case, the battery current \( i_b \) is not equal to \( i_L \) and it has an impulsive behaviour as it is shown in Figure 4.

2.2. EESSS Charge: Layout 1 vs. Layout 2

Let us suppose that an EESSS in charge condition is connected to a layout 1 d.c.-d.c. converter, and that the inductor current \( i_L \) is constantly not null. In this condition, the d.c.-d.c. converter operates as a step-down stage (\( T_2 \) is inhibited) and its output voltage (i.e., battery voltage \( U_b \)) still depends only upon the \( T_1 \) duty cycle \( D \), and it is given by:

\[
U_b = D \cdot U_o
\]
Consequently, the battery voltage $U_b$ is always lower than the input voltage $U_o$. In the EESSS charge mode this voltage behaviour has a key-role because the power flow from the grid to the battery is always guaranteed, so that the charge operation is possible directly from the grid. The battery current is unidirectional and non-impulsive (see Figure 5).

**Figure 4.** Layout 2 discharge operation: current and voltage waveforms (continuous conduction).

**Figure 5.** Layout 1 charge operation: current and voltage waveforms (continuous conduction).

In the same charge above mentioned condition, a layout 2 converter, operates as a step-up converter ($T_1$ is inhibited) and the output voltage $U_b$ is given by ($D$: $T_2$ duty cycle):

$$U_b = U_o / (1 - D)$$

(4)

Therefore the battery voltage $U_b$ is greater than $U_o$, as in the discharge operation; being $U_o$ generally imposed by grid interface requirements, $U_b$ maximum value could result in demanding specifications for EESSS and connected electrical installation. Moreover, the current is again pulsed, as it is shown in Figure 6. Hence, Layout 1 configuration is preferable in both charge and discharge operation.
3. d.c.-d.c. Converter Control

Being Layout 1, as explained above, more convenient to interface an EESSS with an inverter, in the following, the analysis of Layout 1 is deepened to take into account the operation at discontinuous conduction mode.

3.1. d.c.-d.c. Converter Control: Discontinuous Discharge Mode

With reference to Layout 1 of Figure 2a and to discharge operation, let us suppose that the average load current $I_o$ is low enough to cause the zeroing of the inductor current $i_L$. The converter operates therefore in discontinuous discharge mode (see Figure 7).
In this condition [12] the converter output voltage does not depend only upon the \( T_2 \) duty cycle \( D \) but upon the supplied current \( I_o \) as well. According to Figure 7, the average value of the supplied current is given by:

\[
I_o = \frac{1}{T} \int_0^T i_o(t) \, dt = \frac{\Delta \cdot I_{i_p}}{2} = \frac{\Delta \cdot U_b \cdot D \cdot T}{2L}
\]

(5)

Since the inductance net flux variation is null over the period \( T \), it results:

\[
U_b \cdot DT + (U_b - U_o) \cdot \Delta \cdot T = 0
\]

(6)

and then, by solving (6) with respect to \( U_o \), it results:

\[
U_o = U_b \cdot \frac{D + \Delta}{\Delta} \geq U_b \cdot \frac{1}{1 - D}
\]

(7)

since it can be verified that \((D + \Delta)/\Delta \geq 1/(1 - D)\) for \( 0 \leq D \leq 1 \); the transition from the continuous to the discontinuous mode corresponds to the limit condition \( \Delta_{\lim} = 1 - D \). Inserting \( \Delta_{\lim} \) in Equation (5) and taking into account that Equation (1) still holds in the limit condition, so \( U_b = (1 - D) \cdot U_o \) can be substituted in Equation (5), the discontinuous limit current is obtained:

\[
I_{o,\text{lim}} = \frac{(1 - D)^2 \cdot D \cdot U_o \cdot T}{2L}
\]

(8)

Maximizing Equation (7) with respect to \( D \), the maximum value \( I_{o,\text{lim},M} \) is obtained for \( D_M = 1/3 \), i.e.:

\[
I_{o,\text{lim},M} = I_{o,\text{lim}}(D_M) = \frac{2U_o \cdot T}{27L}
\]

(9)

then, Equation (8) can be rewritten as:

\[
\frac{I_{o,\text{lim}}}{I_{o,\text{lim},M}} = \frac{27}{4} (1 - D)^2 D
\]

(10)

by replacing Equation (7) into Equation (5) and dividing by Equation (9), the average output current can be expressed as:

\[
\frac{I_o}{I_{o,\text{lim},M}} = \left( \frac{U_b^2 \cdot D^2 \cdot T}{2L(U_o - U_b)} \right) \left( \frac{2U_o \cdot T}{27L} \right) = \frac{27}{4} D \left( \frac{U_b}{U_o} \right)^2 \left( 1 - \frac{U_b}{U_o} \right)
\]

(11)

that, solved with respect to \( U_o \), yields:

\[
U_o = \frac{27D^2/2}{\sqrt{(27D^2 + I_o/I_{o,\text{lim},M}) \cdot I_{o,\text{lim},M} - I_o/I_{o,\text{lim},M}}} \cdot U_b
\]

(12)

whereas, solved with respect to \( D \), it allows determining its value as a function of \( U_o/U_b \) and \( I_o/I_{o,\text{lim},M} \):

\[
D = \sqrt{\frac{4}{27} \frac{I_o}{I_{o,\text{lim},M}} \frac{U_o}{U_b} \left( \frac{U_o}{U_b} - 1 \right)}
\]

(13)

According to Equation (12), in the discontinuous mode operation, since \( D \) is constant and by decreasing \( I_o \), the output voltage exceeds the value given by Equation (1) and becomes higher and
higher. For instance, Figure 8 shows that, for $D = 42.9\%$, $I_o/I_{o,lim,M} = 33.1\%$ (point P in discontinuous mode operation), the voltage ratio $U_o/U_b$ rises to 250% with respect to 175%, corresponding to continuous mode operation.

**Figure 8.** Layout 1 discharge operation: $D$ as a function of current $I_o/I_{o,lim,M}$ for different $U_o/U_b$ values.

**Figure 9.** Outline of the feedback voltage control in discharge condition.

**Figure 10.** Elaboration of duty cycle control signal by a PWM technique.
Provided that discontinuous conduction mode could occur at low load operation, output voltage regulation requires a feedback control of duty-cycle, outlined in Figure 9. The driving technique is based on the PWM approach, as it is represented in Figure 10: it can be easily verified that the switch duty cycle is \( D = \frac{t_{on}}{T} = \frac{v_{cont}}{V_{st}} \), with \( v_{cont} \) and \( V_{st} \) control signal voltage and voltage peak value of a reference sawtooth wave \( v_{st} \) with period \( T \).

3.2. d.c.-d.c. Converter Control: Discontinuous Charge Mode

With reference to Layout 1 of Figure 2a and to discharge operation, let us suppose that the average current \( I_o \) flowing from the grid to the battery is low enough to cause the zeroing of the inductor current \( i_L \). The converter operates therefore in discontinuous charge mode (see Figure 11) so that the converter output voltage depends upon both the \( T_1 \) duty cycle \( D \) and the input current \( I_o \).

\[ \Delta \left( T_U \right) = \frac{0}{\Delta \left( U_{bo} \right)} \]  

By imposing that the inductance net flux variation is null over the period \( T \), it results:

\[ -U_b \cdot \Delta \cdot T + (U_o - U_b) \cdot DT = 0 \]  

and then, by solving Equation (14) with respect to \( \Delta \):

\[ \Delta = \frac{U_o - U_b}{U_b} D = \frac{1}{U_b/U_o} - 1 \]  

By solving in turn Equation (15) with respect to \( U_b/U_o \) it yields (taking into account that \( \Delta < 1 - D \) and \( 0 \leq D \leq 1 \)):

\[ \frac{U_b}{U_o} = \frac{D}{D + \Delta} > \frac{D}{D + (1-D)} = D \]  

The voltage ratio is higher than the corresponding value Equation (3) for continuous conduction mode. According to Figure 11, the average value of the current supplied from the converter to the battery is:

**Figure 11.** Layout 1 charge operation: current and voltage waveforms (discontinuous conduction).
Replacing in Equation (17) the duty cycle limit value $\Delta_{\text{lim}} = 1 - D$, the current limit value corresponding to the transition from the continuous to the discontinuous conduction mode is obtained:

$$I_{b,\text{lim}} = D \cdot (1 - D) \cdot U_o \cdot T / (2L)$$  \hspace{1cm} (18)

By maximizing Equation (18) with respect to $D$, the maximum value $I_{b,\text{lim},M}$ is obtained for $D_M = 1/2$, i.e.: 

$$I_{b,\text{lim},M} = I_{b,\text{lim}}(D_M) = U_o \cdot T / 8L$$  \hspace{1cm} (19)

By solving Equation (17) with respect to $\Delta$ and taking into account (19) it yields:

$$\Delta = \frac{I_b / I_{b,\text{lim},M}}{4D}$$  \hspace{1cm} (20)

The substitution of Equation (20) into Equation (16) gives $U_b/U_o$ as a function of $D$ and of $I_b/I_{b,\text{lim},M}$:

$$\frac{U_b}{U_o} = \frac{D^2}{D^2 + I_b / (4I_{b,\text{lim},M})}$$  \hspace{1cm} (21)

Finally, the solution of Equation (21) with respect to $D$ allows to express it as a function of $U_b/U_o$ and $I_b/I_{b,\text{lim},M}$:

$$D = \sqrt{\frac{I_b}{4I_{b,\text{lim},M}}} \frac{U_b / U_o}{1 - U_b / U_o}$$  \hspace{1cm} (22)

According to Equation (21), in the discontinuous mode operation since $D$ is constant and by decreasing $I_b$, the battery voltage $U_b$ exceeds the value given by Equation (3) and gets closer and closer to $U_o$. For instance, Figure 12 shows that, for $D = 25\%$, $I_b/I_{b,\text{lim},M} = 25\%$ (point P in discontinuous mode operation), the voltage ratio $U_b/U_o$ rises to 50$\%$ with respect to 25$\%$, corresponding to continuous mode operation.

![Figure 12](image-url)  

Figure 12. Layout 1 charge operation: $D$ as a function of $I_b/I_{b,\text{lim},M}$ for different $U_o/U_b$ values.
Hence, once again, a feedback voltage control is necessary, to regulate dynamically the duty cycle \( D \), as it is shown in Figure 13, where a current control has been added, to regulate the battery charge current. The duty cycle is adjusted by a PWM technique, as mentioned in Section 3.1.

![Figure 13. Outline of the feedback voltage control in charge condition.](image)

4. Full Bridge Inverter Control

The second conversion system in a two-stage inverter, is a full bridge inverter which as well as the a.c./d.c. current conversion has to control the flux of the active power and the reactive one from the EESSS to the grid and vice versa. The main control structures to regulate the power flux by means the full bridge inverter are presented in the following.

\( P/Q \) Control Structures

The power exchange between the inverter and the grid can be described by the simple equivalent circuit of Figure 14a.

![Figure 14. (a) Inverter equivalent circuit; (b) Phasor diagram related to voltage and current components.](image)

The \( P/Q \) control strategy is the chief one for on-grid EESSS installations (conversely, \( V/f \) control is generally adopted for islanding operation). By means of simple geometric considerations on the phasor diagram of Figure 14b, related to the circuit of Figure 14a, the following equations can be derived:
\[
I_d = I \cos \phi = \frac{U_{di}}{\sqrt{3}X} = \frac{U_i \sin \delta}{\sqrt{3}X} \quad I_q = I \sin \phi = \frac{U_{qi} - U_G}{\sqrt{3}X} = \frac{U_i \cos \delta - U_G}{\sqrt{3}X}
\]

\[
P = \sqrt{3} U_G I_d = \frac{U_G U_i \sin \delta}{X} \quad Q = \sqrt{3} U_G I_q = \frac{U_G (U_i \cos \delta - U_G)}{X}
\]

Assuming the angle \( \delta \) to be small, approximations \( \sin \delta \approx \delta \) and \( \cos \delta \approx 1 \) can be applied to Equation (23), which can be rewritten as:

\[
P = \frac{U_G U_i \sin \delta}{X} \approx \frac{U_G U_i \delta}{X} ; Q = \frac{U_G (U_i \cos \delta - U_G)}{X} \approx \frac{U_G (U_i - U_G)}{X}
\]

According to Equation (24), active and reactive power flow can be managed adjusting inverter voltage phase displacement \( \delta \) and amplitude \( U_i \), respectively. Such quantities can be adjusted in turn according to the scheme outlined in Figure 15: the current errors \( \Delta I_d \) and \( \Delta I_q \) of the inverter current components \( I_d \) and \( I_q \) with respect to their reference values \( I_{d,ref} \) and \( I_{q,ref} \) are used as feedback signals to control \( \delta \) and \( U_i \) respectively, according to first two equations in Equation (23), and consequently \( P \) and \( Q \). Current reference values \( I_{d,ref} \) and \( I_{q,ref} \) are in turn obtained by elaborating active and reactive power errors \( \Delta P \) and \( \Delta Q \) of the actual power components \( P \) and \( Q \) with respect to their reference values \( P_{ref} \) and \( Q_{ref} \). Of course, such strategy relies on the synchronization between the inverter. To such purpose, the grid phase voltage phasor \( U_G/\sqrt{3} \), namely its amplitude and instantaneous phase, must be identified, by elaborating the grid voltage measurements \( u_{GAB} \), \( u_{GBC} \), \( u_{GCA} \) by a Phase-Locked Loop (PLL) technique [13]. Similarly, the actual inverter current components \( I_d \) and \( I_q \) with respect to the grid phase voltage reference frame are determined by the elaboration of the phase current measurements (not reported in Figure 15 for sake of clearness).

Assuming that other sources could contribute to the DC link, an alternative control strategy can be devised for the two-stage converter, aimed at providing stability and fast response at the same time coordinating the d.c./d.c. converter and the inverter operation. Accordingly, the former is driven to follow the active power reference to be injected at the d.c. link, whereas the latter is committed to following the reference value for the d.c. link voltage \( U_o \), satisfying the reactive power demand at the same time.
5. Massive Energy Stationary Storage Experience in Italy

“Terna Storage” (a group of the Italian TSO Terna) has foreseen a massive installation (130 MW) of EESSS on the HV electric grid: at the moment, three 12 MW/12 MW/10.8 MW installations with sodium sulphide (NaS) [1–6] batteries for energy storage have been already installed. For these systems, the charge/discharge time is rather long, (*i.e.*, 8 h), so that they have been named “energy intensive” or “energy-driven” (see Figure 16a). Another 16 MW installation has been realized with sodium nickel chloride [14] (see Figure 16b) and lithium-ion technologies with the aim of network services, which involves shorter charge/discharge times, so that they are called “power intensive” or “power-driven”.

![Image of NaS EESSS](image1)

![Image of Zebra EESSS](image2)

**Figure 16.** (a) Terna *energy intensive* EESSS installation in Ginestra, Italy; (b) Terna *power intensive* EESSS installation in Codrongianos, Italy.

The PCS configuration for the above mentioned installations are based on two-stage inverter, with voltage feed-back control. Thanks to the experience matured by the Italian industry on the inverter field related to the Photovoltaic plants, the nowadays inverter technology allows to reach very good performances. For the EESSS projects, *Terna Storage* standardized the inverter performances as it is reported in Table 2.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal efficiency</td>
<td>≥95.5%</td>
</tr>
<tr>
<td>Response time 0 ÷ 100%</td>
<td>≤80 ms</td>
</tr>
<tr>
<td>Phase inversion time (−100 ÷ 100%)</td>
<td>≤100 ms</td>
</tr>
<tr>
<td>Nominal load current THD</td>
<td>≤3%</td>
</tr>
<tr>
<td>Partial load (20%) current THD</td>
<td>≤5%</td>
</tr>
<tr>
<td>No-load Voltage THD</td>
<td>≤3%</td>
</tr>
<tr>
<td>Voltage regulation accuracy</td>
<td>±1%</td>
</tr>
<tr>
<td>Frequency regulation accuracy</td>
<td>±0.1%</td>
</tr>
<tr>
<td>Power regulation accuracy</td>
<td>±2%</td>
</tr>
<tr>
<td>Availability</td>
<td>≥99.5%</td>
</tr>
</tbody>
</table>

Table 2. *Terna Storage* standardized inverter performances.
These values are referred to the complete system made by PCS and MV/LV transformer. The voltage total harmonic distortion (THD) and current one are sensibly better than the IEEE 1547 and IEC 61727 [15] prescriptions, which consider a THD ≤ 5% at the nominal load.

The availability of 99.5% is obtained by means of an inverter modular structure, with a redundancy of N-1 or higher. Consequently both the conversion system of the two-stage inverter (i.e., the d.c.-d.c. converter and the d.c.-a.c. one) consists of elements in parallel whose power ranges between 250 kVA and 500 kVA. With this configuration the fault of a single element (N − 1 fault condition) does not cause the operation interruption and the return of operation can be managed automatically. The fault of two components, (N − 2 fault condition) could involve a reduction of the power exchanged with the grid, but it does not involve the out of service of the entire system. Because of the high availability of the MT/BT transformer, a redundancy of it is not necessary and has not been foreseen.

6. Discussion and Conclusions

This paper aims at giving the readers a guide for the electrochemically stored energy conversion. The pros and cons of different conversion layouts have been analysed and the more suitable conversion architecture has been identified. For a safe operation of the entire system in case of discontinuous mode of the converter, a voltage control strategy have been presented. Moreover, the chief control scheme to regulate the active and reactive power exchange between the conversion system and the grid has been shown. The main aim of this work is to focus on the necessary elements which must be taken into account when a power conversion architecture has to be chosen, in the light of the PCS state of the art namely:

- The use of a two-stage converter is more convenient in order to avoid an oversized inverter. The first stage is made by a d.c.-d.c. converter, in order to maintain a constant continuous voltage reference for the inverter d.c. side. The second stage is represented by the d.c.-a.c. inverter itself;
- In order to avoid an impulsive behaviour of the battery current, the first stage of the two-stage converter has to be constituted by a layout 1 d.c.-d.c. converter;
- If the battery current is too low, the converter could work in discontinuous mode, so that the voltage references for the battery and the inverter cannot be controlled just by means of the converter piloting. Therefore, a feed-back voltage control is necessary to regulate the voltage reference in case of discontinuous mode;
- In order to regulate the active and reactive power exchange between the battery and the grid, it is possible to act on the inverter direct and quadrature current components by means of a suitable control system.

List of Symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EESSS</td>
<td>Electrochemical Energy Stationary Storage System;</td>
</tr>
<tr>
<td>PCS</td>
<td>Power Conversion System;</td>
</tr>
<tr>
<td>HV</td>
<td>High voltage;</td>
</tr>
<tr>
<td>MV</td>
<td>Medium voltage;</td>
</tr>
<tr>
<td>LV</td>
<td>Low voltage;</td>
</tr>
<tr>
<td>u</td>
<td>voltage instantaneous value;</td>
</tr>
</tbody>
</table>
\(i\) current instantaneous value;
\(u_{x,p}\) voltage peak value referred to the x component;
\(i_{x,p}\) current peak value referred to the x component;
\(U_o\) average voltage value referred to the converter output side;
\(U_b\) average voltage value referred to the battery output side;
\(I_o\) average current value referred to the converter output side;
\(I_b\) average current value referred to the battery output side;
\(D_1, D_2\) d.c.-d.c. converter diodes;
\(i_{D1}, i_{D2}\) d.c.-d.c. converter diode currents;
\(t_{xon}\) “on state time” of the switch \(T_x\);
\(t_{off}\) “off state time” of the switch \(T_x\);
\(T\) whole commutation time of the switch \(T_x\);
\(D\) \(t_{xon}/T\) Duty cycle of the d.c.-d.c. converter;
\(I_q\) inverter quadrature current components;
\(I_d\) inverter direct current components;
\(U_i\) phasor of the inverter voltage;
\(U_G\) phasor of the grid voltage;
\(THD\) Total Harmonic Distortion;
\(m_a\) amplitude modulation index;
\(m_f\) voltage modulation index;
PWM Pulse With Modulation;
PLL Phase Locked Loop device.

Conflicts of Interest

The authors declare no conflict of interest.

References


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