ANALYSIS OF FIVE-LEVEL UNIDIRECTIONAL RECTIFIERS

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This paper presents a new five-level rectifier structure which is compared with a well known solution. Flying capacitor and coupled inductor concepts are used and discussed for the two structures. Control strategies and simulation results are presented in order to show the operation mode and performances of each structure. Advantages and disadvantages are presented in view of the total power losses in the semiconductor devices, the maximum output power and the type of application where these converters are best suited.

1. INTRODUCTION

In order to obtain high power rectifiers it was necessary to increase the current and voltage capability for the semiconductor devices. For medium voltage applications, the semiconductor devices have high voltage ratings a fact that translates to increased equipment cost. Multilevel rectifiers were created as a solution to reduce the voltage and current stress of the semiconductor devices compared with classical solutions. For some multilevel rectifiers it is possible to increase the apparent frequency of the input voltage, a fact that leads to the reduction of the total harmonic distortion factor.

These observations led to the development of several multilevel structures during the last years [1, 2]. The development of unidirectional multilevel rectifiers started in 1996 with the structure called Vienna 1 that was proposed by Kolar [3]. The single phase bridge arm contains a single transistor that works on the entire cycle and six diodes. Following the principles given by this structure, several other structures were created that had double-boost effect, lower losses in the insulated gate bipolar transistor (IGBT) devices and the possibility to increase the maximum output power [4, 5]. In [6] it was presented a comparison between several known three level and five level rectifiers and a new flying capacitor rectifier concept. The comparison was made regarding the use of these converters.

Another class of multilevel converters introduces the coupled inductor concept [12, 13]. This type of converters offers an increased number of voltage levels, lower current stress in the semiconductor devices and better voltage properties. In order to combine the advantages given by the structures that do not use the coupled inductor concept and those that do, hybrid structures were developed [14].

In this paper the rectifiers obtained from the Five Level ANPC with flying capacitor (5L-ANPC-FC) and the five level ANPC with coupled conductor (5L-ANPC-CI) converters are presented. The 5L-ANPC-CI rectifier is a new structure. This paper is organized as follows. The operation mode and features for the two rectifiers are presented in Section 2 and 3. Section 4 presents a rectifier control method, while Section 5 contains a theoretical method to estimate the power losses in the semiconductor devices. The last section presents a comparative study between the two structures in view of the total power losses and offer guidelines regarding the use of these converters.

2. FIVE-LEVEL ANPC-FLYING CAPACITOR RECTIFIER

The unidirectional 5L-ANPC-FC rectifier was developed from the inverter with the same name [10]. It is made from four bidirectional switches S5-S8, four unidirectional ones S1-S4 and one flying capacitor (Fig.1). The result is a structure that provides a voltage \( u_a \) with five levels measured after the line inductance \( L \). This leads to the reduction of the size of \( L \).

The devices S1-S4 switch with the frequency of the line voltage \( u_a \) and form the high voltage stage (HV). The devices S5-S8 switch with the frequency of the carrier wave and form the low voltage stage (LV). Also for this structure the apparent switching frequency \( f_{sp} \) in the input and output passive components is two times larger than the frequency of the carrier waves.

In order to provide a better understanding of the operation mode, the current paths for the positive and negative sides of the input voltage \( u_a \) are given (Fig. 2, Fig. 3). By taking into consideration the switching functions for the active devices: \( f_1 \) for \( S_5 \) and \( f_2 \) for \( S_7 \) the resulting input voltage \( u_a \) can be expressed (1). The \( f_1 \) function takes the value 1 when \( S_5 \) is on, while \( f_2 \) has the value 1 when \( S_7 \) is on.

When the input voltage \( u_a \) is positive, the current that charge the filter \( – L \) circulates through two paths: transistor \( S_6 \) – transistor \( S_3 \) – \( S_7 \) or diode \( D_7 \) – flying capacitor – transistor
Analysis of five-level unidirectional rectifiers

\[ u_C = \left( u_{dc} / 4 \right) \cdot \left( f_1 + f_2 \right) \quad u_a > 0 \]

\[ u_C = \left( u_{dc} / 4 \right) \cdot \left( f_1 + f_2 - 2 \right) \quad u_a < 0 \]
3. FIVE-LEVEL ANPC-COUPLED INDUCTOR (CI) RECTIFIER

The unidirectional 5L-ANPC-CI rectifier is developed from the inverter with the same name [14] and it is first presented in this paper. It is made from four bidirectional switches $S_5$–$S_8$ that form the low current stage (LC), four unidirectional ones $S_1$–$S_4$ that form the high current stage (HC) and one coupled inductor (Fig. 4). Similar to the previous structure, the 5L-ANPC-CI also provides five voltage levels for the voltage $u_C$. The coupled inductor is used to create the five voltage levels of $u_C$ and to reduce the current through the devices $S_5$–$S_8$ to half of $i_a$ (2). In (2), $i_{L1}$ and $i_{L2}$ are the current through the windings of the coupled inductor and $i_a$ is the input current. The current paths are presented in order to describe the operation of this rectifier (Fig. 5 and Fig. 6).

\[ i_{L1} = i_{L2} = i_a/2 \]  

(2)

The apparent switching frequency of $u_c$ is two times larger than the switching frequency (3), a property that leads to the reduction of the total harmonic distortion (THD) and of the size of the line inductance required.

As it can be observed, the coupled inductor is used on all the stages and the current circulates through three semiconductor devices similar to the flying capacitor topology. Because of these properties, the conduction losses are reduced and the apparent switching frequency is increased.

\[ f_{ap} = 2 \cdot f_{sw} \]  

(3)

Similar to the previous structure, when the input voltage $u_a$ is positive the current that charges the filter $L$ circulates through two paths: coupled inductor – transistor $S_6$ – $S_3$ or coupled inductor – transistor $S_8$ – $S_3$ and the $u_{dc}/4$ level is obtained. When $S_6$ and $S_8$ are both in conduction the input voltage $u_c$ is equal to zero. The load current circulates through the following two paths: coupled inductor – diode $S_3$ – $S_1$ or coupled inductor – transistor $S_7$ – $S_1$ and the $u_{dc}/2$ level results.

On the negative side of $u_a$ this rectifier provides the following paths for the charging current: $S_2$ – transistor $S_5$ – coupled inductor or $S_2$ – transistor $S_7$ – coupled inductor and the $-u_{dc}/4$ level is obtained. When both transistors are in...
The conduction zero level is obtained. The load current circulates through: $S_4$ – diode $S_6$ – coupled inductor or $S_4$ – diode $S_8$ – coupled inductor and provides the $-u_{dc}/2$ voltage level.

The resulting input voltage $u_c$ has the same representation like in the previous structure regarding the switching functions (1) and switching pattern for the four transistors is also similar. The next section presents two control methods for this rectifier and a simulation result that validates this theoretical study.

### 4. RECTIFIER CONTROL

The control of the rectifiers can be made in two ways:
- indirectly with the compensation of $u_{ref}$
- directly with a hysteresys comparator.

The indirect control is similar to the inverter PWM control with the difference that the reference wave is replaced with a control wave $\alpha$ obtained from an open loop (Fig. 7a). This method has the advantage that the frequency of the carrier waves is known and the obtained THD is low, but requires a greater computational effort compared with the direct method.

The direct method (Fig. 7b) presents the disadvantage that the switching frequency varies in a large band and can not be controlled by the user.

In Fig. 7, $u_{ref}$ is the output reference voltage, $u_a$ is the input voltage, $i_a$ is the input current, $U_{aV}$ is the peak value of $u_a$ while $u_{dc}$ is the output voltage. Also VR is a voltage regulator, CR a current regulator, HC a hysteresys comparator and LIM1, LIM2 are limitation blocks.

The output of the indirect control ($\alpha$) is compared with two positive carrier waves phase-shifted with half of switching period.

In Fig. 8 simulated results for the indirect control method applied to the ANPC-CI rectifier are presented. The transistor of device $S_5$ switches $u_{dc}/2$, but has a reduced current value compared to the diode $S_2$ that switch at zero voltage but with an increased current. This property leads to reduced and well distributed losses.

Fig. 7 – Rectifier control: a) indirect method; b) direct method.

Fig. 8 – Simulated results for the 5L-ANPC-CI rectifier ($u_{dc}=800$ V, $i_{rms}=100$ A, $f_{sw}=5$ kHz):
- current through the transistors of the devices $S_5$ and $S_6$;
- current through the devices $S_2$ and $S_5$;
- voltage switched by the devices $S_2$ and $S_5$.

### 5. POWER LOSSES ESTIMATION METHOD

The maximum output power is dependent of the conduction and switching power losses [15–17]. This estimation has been done by using a lookup table for the thermal and electrical parameters of each device based on the datasheet graphical dependence.

In order to simplify this model the following hypothesis were made:
- the output current is sinusoidal;
- the dead time for the transistors is neglected.

**Conduction losses.** The conduction losses for an IGBT device can be calculated using the dependence between the transistor saturation voltage $V_{CE(sat)}$ and the collector current ($I_C$) at any given moment

$$P_{cT} = V_{CE(sat)} \cdot I_C.$$  

The antiparallel diode conduction losses are computed in a similar fashion using the datasheet dependence between the diode voltage drop ($V_D$) and the forward current ($I_D$)

$$P_{cD} = V_D \cdot I_D.$$  

**Switching losses.** The switching losses for the transistor ($P_{swT}$) are computed by taking into consideration the dependence between the turn-on energy ($E_{ON}$), the turn-off energy ($E_{OFF}$) and the collector current ($I_C$)

$$P_{swT} = (V_{Tsw} / V_{CE}) \cdot (E_{ON}(I_C) + E_{OFF}(I_C)) \cdot f_{sw}.$$  

The switching losses for the diode ($P_{swD}$) are related to the recovery energy ($E_{REC}$) (7).

$$P_{swD} = (V_{Dsw} / V_{CE}) \cdot E_{REC}(I_D) \cdot f_{sw}.$$  

The total power losses in each device represent the sum of the conduction and switching losses for the transistor (8) and for the diode (9).
6. COMPARATIVE STUDY

This comparative study is focused on the power loss distribution in the semiconductor devices, the total power losses and the output power obtained for the two five level rectifier structures for a low voltage application (Fig. 9).

![Simulated distribution of losses using Eupec FS200R06KL4 IGBT devices (\(U_{DC} = 800\) V, \(f_{SW} = 10\) kHz, \(I_{RMS} = 100\) A): a) 5L-ANPC-FC; b) 5L-ANPC-CI.]

![Simulated results for both rectifiers (\(U_{DC} = 800\) V, \(I_{RMS} = 100\) A, \(f_{SW} = 5\) kHz): a) input voltage \(U_c\) and current \(I_a\); b) Fast Fourier Transform of \(U_c\).]

The main advantage of the 5L-ANPC-FC rectifier is the half reduction of the voltage supported by the switches from the low voltage stage. This property leads to the reduction of the switching losses (6), (7).

The main advantage of the 5L-ANPC-CI rectifier is the half reduction of the current through the switches from the low current stage. This property leads to the reduction of all the losses (8), (9).

Simulated results are shown in order to prove the operation mode and performances given by the two rectifier structures (Fig.10).

Because of these properties the 5L-ANPC-FC rectifier is best suited for a medium voltage application where the reduction of the switched voltage of the semiconductor devices represents an important factor due to the price of such devices.

The 5L-ANPC-CI rectifier presents the best results for a high current application due to the reduction of the current that goes through the devices near the coupled inductor.

The total power losses for the two structures were computed (Table 2).

The maximum output power that can be obtained by the 5L-ANPC-CI converter is larger with 28.8 % compared with the 5L-ANPC-FC converter.

### Table 2

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<tbody>
<tr>
<td>5L-ANPC-CI</td>
<td>187.6</td>
<td>78.2</td>
<td>265.8</td>
</tr>
<tr>
<td>5L-ANPC-FC</td>
<td>323</td>
<td>50.4</td>
<td>373.4</td>
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7. CONCLUSIONS

This paper presented a new structure named the 5L-ANPC-CI rectifier. It was compared with a known structure from the point of view of the power loss distribution and the maximum output power rating.

The new structure presents the following advantages:
- Five voltage levels after the input inductor which leads to a reduced harmonic content;
- The apparent switching frequency is two times larger than the carrier wave frequency;
- Increased output power;
- Half reduced current in the transistors due to the use of the coupled inductor;
- Reduced total power losses.

The ANPC-FC rectifier reduces the voltage supported by the semiconductor devices, a fact that leads to the reduction of the switching losses.

The ANPC-CI rectifier allows the reduction of both switching and conduction losses, making it a better suited structure in case of high current requirements.

A theoretical study regarding the estimation of the power losses in the semiconductor devices has been presented and used to describe the advantages of the two rectifiers.

From the comparison resulted that the ANPC-CI converter has an increased output power compared with the ANPC-FC converter.

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