LOSS BALANCING IN THREE-LEVEL ACTIVE-NEUTRAL-POINT-CLAMPED CONVERTER

DAN FLORICĂU [1], DAN OLARU [2], ELENA FLORICĂU [3], IOAN POPA [4]

Keywords: Multilevel Converters, NPC Converter, ANPC Converter, PWM Strategies, Loss Distribution.

The 3L-NPC (Neutral-Point-Clamped) is the most popular multilevel converter used in high-power medium-voltage applications. An important disadvantage of this structure is the unequal distribution of losses among the switches. The performances of 3L-NPC structure were improved by developing the 3L-ANPC (Active-NPC) converter which has more degrees of freedom. In this paper the switching states and the loss distribution problem are studied for two PWM strategies in a STATCOM application. The PSIM simulation results are shown in order to validate the studied PWM strategies.

1. INTRODUCTION

Reactive power converter compensation is one of the most important actions to control power systems on transmission and distribution level. It allows better stability of overall system, decreases losses and permits to maintain better voltage profile. The compensated power system is less prone to failure than a non compensated one. For the last fifteen years there have been tendencies to replace the traditional compensators with FACTS (Flexible Alternating Current Transmission System) devices that are based on power converters. The shunt capacitors and inductances can be replaced with STATCOM (Static Compensator) and series capacitors SSSC (Series Static Synchronics Compensator). These devices have advantages of fast response and they need a considerably smaller amount of real estate for their installation.

[1]"Politehnica" University of Bucharest, 313 Spl. Indep., 060042 Bucharest, df@conv.pub.ro
[2] "Politehnica" University of Bucharest, 313 Spl. Indep., 060042 Bucharest, danolaru@apel.apar.pub.ro
[3] "Politehnica" University of Bucharest, 313 Spl. Indep., 060042 Bucharest, elena_floricau@conv.pub.ro
[4] University of Craiova, 107 Bd. Decebal, 200440 Craiova, ipopa@elth.ucv.ro

Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **54**, *3*, p. 281–290, Bucarest, 2009

Their main drawbacks are the switching and the conduction losses. Moreover, voltage rating of switching devices is not high enough. To increase the voltage rating of the power converter and so of the overall FACTS controllers, different multilevel topologies have been developed [1].

The first developed multilevel topology consisted in a serial connection of single-phase inverters with DC separate sources [2]. This structure was followed by a stacked commutation cells concept in order to obtain a multilevel conversion (SC – Stacked Cells) [3-4]. Following the SC structure, a new multilevel NPC (Neutral-Point-Clamped) topology was developed [5]. This is the most popular multilevel conversion structure.

Later, another invention [6] introduced the concept of the multilevel converter with flying-capacitors (FC-Flying Capacitor). In the range of low and moderate switching frequencies (200Hz-1kHz), the 3L-NPC converter is especially advantageous because of the required flying-capacitor size, which is inversely proportional to the switching frequency. The performances of 3L-NPC structure were improved by developing the 3L-ANPC (Active-NPC) converter [7-8]. This converter has more degrees of freedom and can be controlled by different PWM strategies [9]. Recently, a new three-level structure named 3L-SNPC (Stacked NPC) was developed [10]. This converter is derivative of the 3L-SC and 3L-NPC concepts and improves the static conversion [11].

The studies made in the paper are focused on the 3L-NPC and 3L-ANPC converters used in a STATCOM application. The switching states and commutations of these converters are analyzed and their influence on the balancing of losses within the converter is explained. The PSIM simulation results are shown in order to validate the PWM strategies (Fig.1) studied for 3L-ANPC converter.

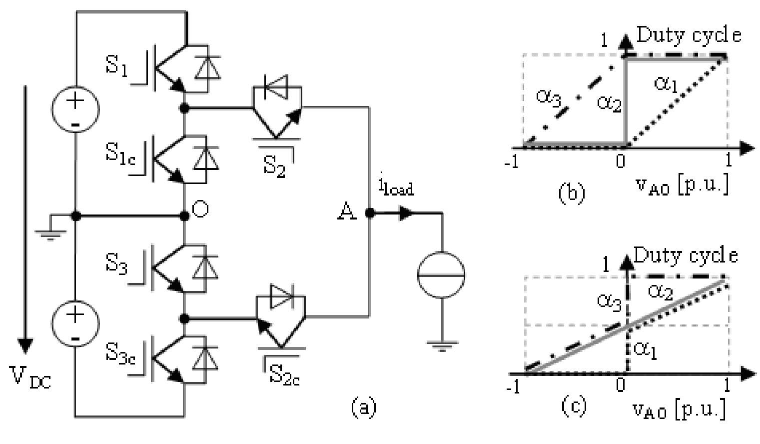

Fig. 1 – Three-level ANPC converter: a) topology, b) PWM-1 strategy and c) PWM-2 strategy.

2. **THREE-LEVEL NPC CONVERTER**

The 3L-NPC is the most popular 3L topology (Fig. 2a). It is composed by four bidirectional switches (S_1, S_{1c}, S_2 and S_{2c}) and two clamp diodes (D_u, D_d). Each bidirectional switch (S) is made of a transistor (T) and an anti-parallel diode (D). The supply voltage source V_{DC} is made of two secondary sources serially connected.

The bidirectional switches form two basic commutation cells: cell-1 (S_1-S_{1c}) and cell-2 (S_2-S_{2c}). These are controlled by α_1 and α_2 duty cycles (Fig. 2b). A sinusoidal PWM strategy [11] was used to analyse the switching states. Thus, the 3L-NPC topology has only three commutation states: P, O and N (Table 1). The existence of a single switching state (O) represents a limitation on the 3L-NPC structure that has direct consequences for the loss distribution among the power devices.

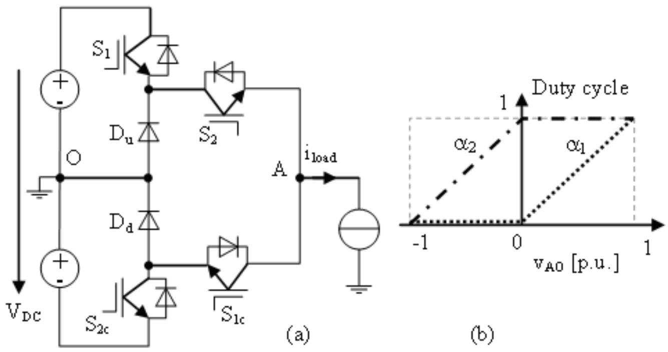

Fig. 2 – Three-level NPC converter and duty-cycle control.

Table 1

Switching sequences of 3L-NPC converter

Output Voltage (v_{A0})	Switching State	Switch Sequence			
		S_1	S_{1c}	S_2	S_{2c}
$-V_{DC}/2$	N	0	1	0	1
0	O	0	1	1	0
$V_{DC}/2$	P	1	0	1	0

The methodology used in the paper to calculate the total losses in power devices was first carried out in [10] and was extended in [11]. By using this methodology it has been observed that the loss distribution depend on the operating points and on the type of the converter.

The 3L-NPC converter is symmetrical. As a result, it is enough to analyse the losses in three switches: S_1 (T_1-D_1), S_2 (T_2-D_2) and D_u.

The Eupec FF200R33KF2C module characteristics [10] have been used for the calculus of total losses in switches. The clamp diodes are also equivalent to the Eupec modules' diodes.

Fig. 3 shows the conduction and switching losses (Pcon and Psw) for the case of 3L-NPC structure at power factor *FP*=0, in a STATCOM application. It has been observed that the inner transistor T_2 (included in S_2) is the most stressed device indifferently of the modulation index (*M*). The loss distribution in the other inner transistor T_{1c} (included in S_{1c}) is similar with the one in T_2 because of the symmetry. Thus, the losses in the most stressed devices limit the switching frequency and the maximum phase current of the entire converter. The other switches are less used.

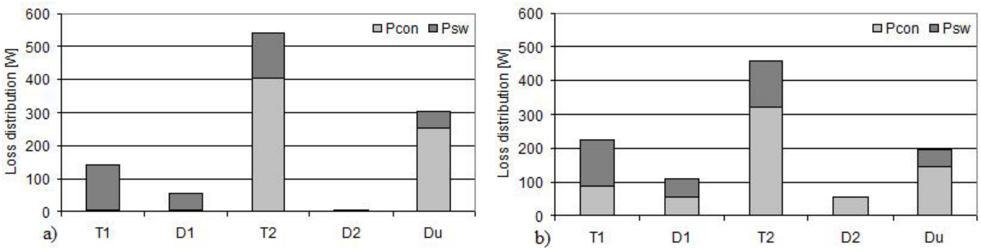

Fig. 3 – Loss distribution in 3L-NPC converter featuring Eupec FF200R33KF2C module (V_{DC}=3000V, I_{rms}=200A, f_s=1000Hz, *PF*=0): a) *M*=0.05, b) *M*=0.95.

3. THREE-LEVEL ACTIVE-NPC CONVERTER

The 3L-ANPC converter is derivative of the 3L-NPC topology (Fig.1a). The 3L-ANPC is composed of six bidirectional switches that support a voltage equal to $V_{DC}/2$. The switches are grouped in three basic commutation cells [cell-1 (S_1-S_{1c}), cell-2 (S_2-S_{2c}) and cell-3 (S_3-S_{3c})], controlled by α_1, α_2 and α_3 duty cycles [Fig.1(b,c)]. Each bidirectional switch (S) is made of a transistor (T) and an anti-parallel diode (D).

In this section, two sinusoidal PWM strategies are analysed and the loss distribution among the power devices for STATCOM application is investigated. These strategies differ by the type and by the number of zero switching states. The different commutations and zero switching states can be used to distribute losses more evenly among the semiconductors.

3.1 PWM-1 STRATEGY

In the case of PWM-1 strategy (Fig. 1b), the cells 1 and 3 switch at a high frequency, while cell-2 switches at a low frequency, equal to the reference voltage frequency. At every moment only a single cell switches.

The PWM-1 strategy compares a sinusoidal reference voltage with two carrier waves [9]. Following the comparison process four switching states are obtained: P, N, O^+ and O^- (Table 2). The switches S_1 and S_2 must be turned on to obtain the state P. The state N is obtained by turning on the switches S_{2c} and S_{3c}. The zero voltage level is obtained with two switching states: O^- and O^+. The state O^- is obtained when the reference voltage is negative, while the state O^+ is obtained when the reference voltage is positive.

For the zero states (O^- and O^+) the load current passes in both directions through the S_{1c} and S_2 or through the S_3 and S_{2c}. As an example, when the transistors T_{1c} and T_2 are turned on, the positive load current passes through D_{1c} and T_2, and the path for the negative one is through D_2 and T_{1c}. The path in both directions through the mentioned switches is an important particularity for the 3L-ANPC structure.

Table 2

Switching sequences of 3L-ANPC PWM-1

Output Voltage (v_{A0})	Switching State	Switch Sequence					
		S_1	S_{1c}	S_2	S_{2c}	S_3	S_{3c}
$-V_{DC}/2$	N	0	0	0	1	0	1
0	O^-	0	0	0	1	1	0
	O^+	0	1	1	0	0	0
$V_{DC}/2$	P	1	0	1	0	0	0

The 3L-ANPC converter is also symmetrical. As a result, it is enough to analyse only the loss distribution in three bidirectional switches: S_1 (T_1-D_1), S_{1c} (T_{1c}-D_{1c}) and S_2 (T_2-D_2).

Fig. 4 shows the conduction and switching losses (P_{con} and P_{sw}) at power factor F_P=0. The transistors T_{1c} and T_3 (due to the symmetry) are the most stressed power devices. In comparison with the 3L-NPC structure, the total losses in the most stressed devices have been reduced with 26% at small modulation index (M=0.05) and with 53% at high modulation index (M=0.95).

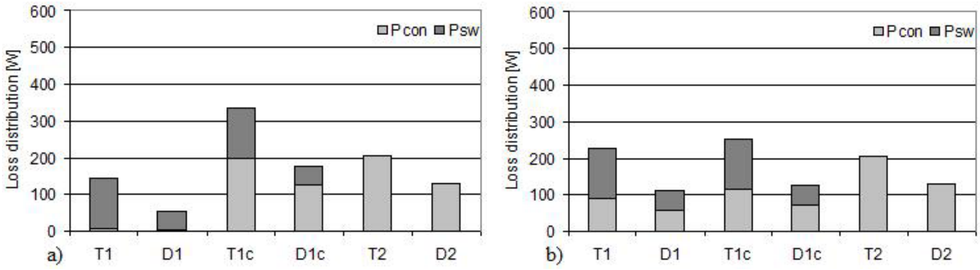

Fig. 4 - Loss distribution in 3L-ANPC PWM-1 featuring Eupec FF200R33KF2C module (V_{DC}=3000V, I_{rms}=200A, f_s=1000Hz, PF=0): a) M=0.05, b) M=0.95.

PSIM program [12] was used to simulate the studied structures. Fig.5 shows the 3L-ANPC PWM-1 simulated results for the output voltage and current waveforms. The cell-2 switches at a low frequency equal to the output voltage frequency. As a result, the bidirectional switches S_2 and S_{2c} have only conduction losses, the switching losses being equal to zero.

The cell-1 and cell-3 switch alternatively at a high frequency, each on a half cycle. As a result, the medium switching frequency on an entire cycle is equal to the half of switching frequency.

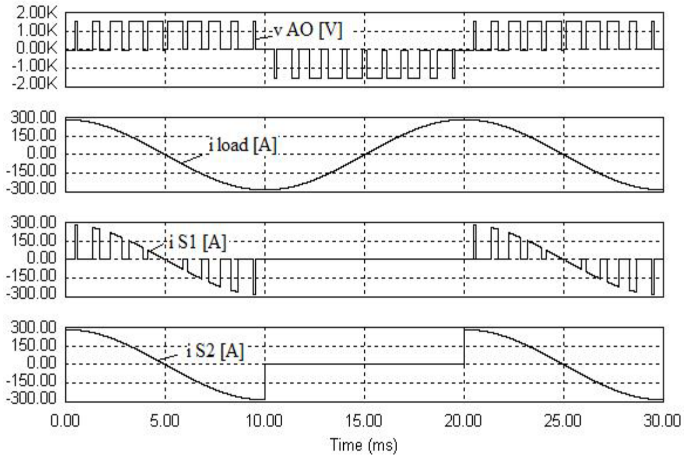

Fig. 5 – Simulated results for the 3L-ANPC PWM-1 ($V_{DC}/2$=1500V, I_{rms}=200A, M=0.8, f_s=1000Hz, PF=0).

3.2 PWM-2 STRATEGY

The PWM-2 strategy allows the natural doubling of the apparent switching frequency. In order to emphasize this advantage, the switching states and sequences are analysed at one switching period T_s (Fig. 6).

The reference voltage S_r is compared with two carrier waves S_{d1} and S_{d2} that are phase-shifted with half of switching period ($T_s/2$). In comparison with the PWM-1 strategy, the PWM-2 one has six switching states: P, N, O_1^-, O_2^-, O_1^+ and O_2^+ (Table 3). The switches S_1, S_2 and S_3 must be turned on to obtain the switching state P. The state N is obtained by turning on the switches S_{1c}, S_{2c} and S_{3c}. In the case of P and N sequences the load current paths through the switches are the same with the PWM-1 strategy.

During the states P and N, two transistors or two diodes are conducting depending on the direction of the phase current. For the zero voltage level, four different control sequences are used: O_1^-, O_2^-, O_1^+ and O_2^+. The states O_1^- and O_2^- are obtained when the reference voltage is negative, while the states O_1^+ and O_2^+ are obtained when the reference voltage is positive. The state O_1^- is obtained when the switches S_{2c} and S_3 are turned on and S_1, S_{1c}, S_2 and S_{3c} are turned off. The state O_2^- is obtained when S_{1c}, S_2 and S_{3c} are turned on and S_1, S_{2c} and S_3 are turned off. The state O_1^+ is obtained when the switches S_{1c} and S_2 are turned on and S_1, S_{2c}, S_3 and S_{3c} are turned off. The paths of the load current are similar to the state O_2^-. The state O_2^+ is obtained when S_1, S_{2c} and S_3 are turned on and the switches S_{1c}, S_2 and S_{3c} are turned off. The paths of the load current are similar to the O_1^- case.

These commutation sequences lead to a natural doubling of the apparent switching frequency similar to the flying-capacitor concept (3L-FC), although the 3L-ANPC structure does not have flying-capacitors.

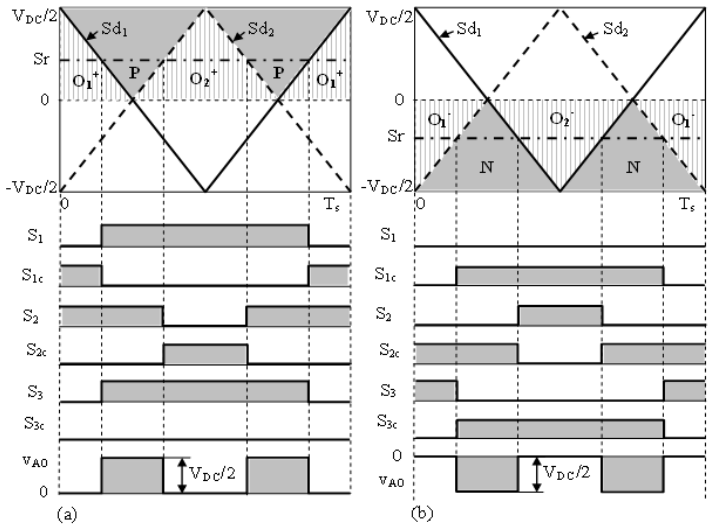

Fig. 6 – PWM-2 strategy for the 3L-ANPC converter: a) $S_r > 0$, b) $S_r < 0$.

Table 3

Switching Sequences of 3L-ANPC PWM-2

Output Voltage (v_{A0})	Switching State	Switch Sequence					
		S_1	S_{1c}	S_2	S_{2c}	S_3	S_{3c}
$-V_{DC}/2$	N	0	1	0	1	0	1
0	O_1^-	0	0	0	1	1	0
	O_2^-	0	1	1	0	0	1
	O_1^+	0	1	1	0	0	0
	O_2^+	1	0	0	1	1	0
$V_{DC}/2$	P	1	0	1	0	1	0

Fig. 7 shows the conduction and switching losses (P_{con} and P_{sw}) at power factor F_P=0. The transistors T_2 (included in S_2) and T_{2c} (due to the symmetry) are the most stressed devices. At small modulation index (M=0.05) the total losses in the most stressed devices are similar with the PWM-1 strategy. At high modulation index (M=0.95) the total losses in the most stressed devices are bigger with 26% in comparison with the PWM-1 strategy.

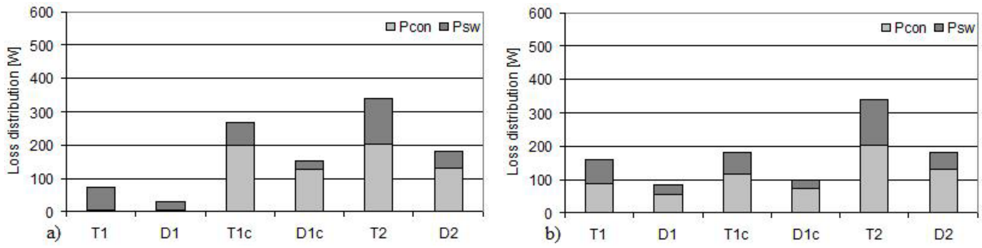

Fig. 7 – Loss distribution in 3L-ANPC PWM-2 featuring Eupec FF200R33KF2C module (V_{DC}=3000V, I_{rms}=200A, f_s=500Hz, PF=0): a) M=0.05, b) M=0.95.

Fig. 8 shows the 3L-ANPC PWM-2 simulated results for the output voltage and current waveforms. On the first half cycle the switches S_1 and S_2 work at the switching frequency f_s (500Hz) and the commutations of S_2 are added to the current waveform of S_1. The switch S_{1c} (included in cell-1) is controlled complementary with S_1. Due to the symmetry S_{2c}, S_{3c} and S_3 switch similarly on the other half cycle. As a result, a doubling of the apparent switching frequency of the output voltage ($2f_s$=1,000Hz) is obtained.

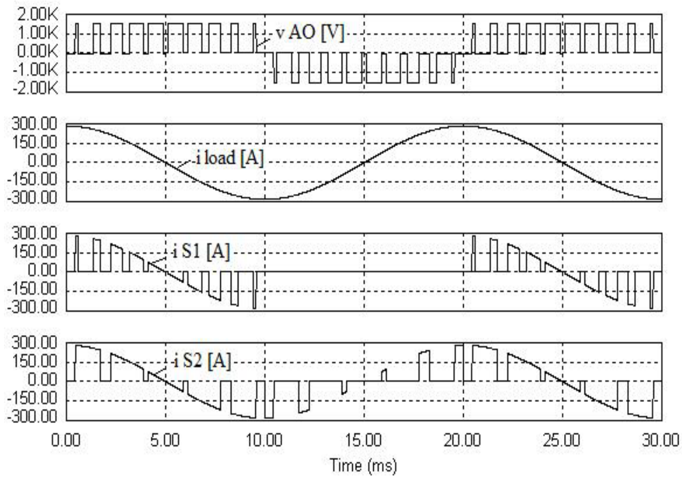

Fig. 8 – Simulated results for the 3L-ANPC PWM-2 (V_{DC}/2=1500V, I_{rms}=200A, M=0.8, f_s=500Hz, PF=0).

4. **CONCLUSIONS**

In this paper the distribution of losses among the semiconductors in the three-level Neutral-Point-Clamped (NPC) converter has been investigated for a STATCOM application. The analysis shows that the distribution is unequal, which severely limits the output power of the converter. To overcome this drawback, the 3L-NPC topology was extended to the 3L-Active-Neutral-Point-Clamped (ANPC) structure. The 3L-ANPC converter has more degrees of freedom and can be controlled by different PWM strategies.

In this paper two PWM strategies have been presented and analyzed in a STATCOM application (PF=0). The PWM-1 strategy has four switching states that lead to reduce the medium switching frequency of the power devices on an entire cycle. For bigger values of modulation index this strategy has a better balancing of total losses in power devices. The PWM-1 strategy is also more simple and easier to implement.

The PWM-2 strategy has six switching states and allows the natural doubling of the apparent switching frequency, similarly to the 3L-FC concept. This represents an important advantage because the 3L-ANPC converter does not have flying-capacitors. However, in the case of PF=0, this strategy does not lead to a better balancing of losses in power devices.

The latter characteristic has made the 3L-ANPC topology an attractive solution particularly for medium-voltage applications.

ACKNOWLEDGMENT

The authors would like to thank the National University Research Council (CNCSIS) for supporting part of this work under project ID_1037 “Researches concerning new static power converters with three levels in order to improve the energy conversion and to assure the quality of electric energy”.

Received on August 12, 2008

REFERENCES

1. J. Rodriquez, J.-S. Lai, F.Z. Peng, *Multilevel Inverters: A Survey of Topologies*, Controls and Applications, IEEE Trans. on Ind. Electronics, **49**, pp. 724-738, 2002.
2. R.H. Baker, *Electric Power Converter*, U.S.Patent 3 867 643, Feb.1975.
3. P. Bhagwat, V.R. Stefanovic, *Generalized structure of a multilevel PWM inverter*, IEEE Industry Applications Society Annual Meeting, 1980, pp.761-76.

4. W. Brumsickle, D.M. Divan, T.A. Lipo, *Reduced Switching Stress in High-Voltage IGBT Inverters via a Three-Level Structure*, Applied Power Electronics Conf. – APEC, 1998, pp.544-550.
5. A. Nabae, I. Takahashi, H. Akagi, *A new neutral-point-clamped PWM inverter*, IEEE Trans. On Ind. Applications, **IA-17**, pp. 518-523, 1981.
6. T.A. Meynard, H. Foch, *Multi-level Conversion: High Voltage Choppers and Voltage-Source-Inverters*, IEEE Power Electronics Specialist Conference, 1992, pp.397-403.
7. T. Brückner, S. Bernet, *Loss balancing in three-level voltage source inverters applying active NPC switches*, Proc. IEEE PESC, Vancouver, 2001, pp.1135-1140.
8. T. Brückner, S. Bernet, H. Güldner, *The Active NPC Converter and Its Loss-Balancing Control*, IEEE Trans.Ind.Electronics, **52**, pp.855-868, 2005.
9. D. Floricau, E. Floricau, M. Dumitrescu, *Natural Doubling of the Apparent Switching Frequency using Three-Level ANPC Converter*, International School on Nonsinusoidal Currents and Compensation – ISNCC, Łagów, Poland, 2008, pp.1-6.
10. D. Floricau, G. Gateau, M. Dumitrescu, R. Teodorescu, *A New Stacked NPC Converter: 3L-topology and control*, 12th European Conference on Power Electronics and Applications – EPE'07, Aalborg, Denmark, 2007, pp.1-10.
11. D. Floricau, E. Floricau, G. Gateau, *Three-level SNPC Commutation Cell: Features and Control*, IEEE International Symposium on Industrial Electronics – (ISIE'08), Cambridge, UK, 2008, pp.44-49.
12. *** Powersim Inc. © 2001-2003, *PSIM Version 6.0*, http://www.powersimtech.com.