Flying Capacitor Topology for Ultra Efficient Inverter Applications

High efficiency and reduced effort for filtering are the main arguments for three-level (3L) topologies. Actually, there are several 3L topologies used in solar applications. The limitation of all Neutral Point Clamped (NPC) three-level topologies is the fact that a 150 Hz ripple has to be filtered with DC capacitors, which are independent on the frequency of the Pulse With Modulation (PWM). With high frequency and utilization of SiC semiconductors it is possible to reduce the size of the output filter, but, however, the DC-capacitors are still required as the same size. There is an alternative Flying-Capacitor (FC) concept in which the 150 Hz ripple is not present. The basic principle of three-level (3L) and four-level (4L) inverter concept is introduced here. **Michael Frisch, Director Product Marketing; Erno Temesi, Chief Engineer; Vincotech Germany and Hungary**

The Neutral Point Clamped (NPC) inverters are widely used in highly efficient solar, UPS and other power electronics applications. This topology (Figure 1) provides advantages in switching losses in a reduced size of the inductor. However, there is one disadvantage to be named, which is the voltage ripple of 3x line frequency (e.g. 3 x 50 Hz => 150 Hz) in the DC bus. This results in an additional effort for DC capacitors to filter the ripple.

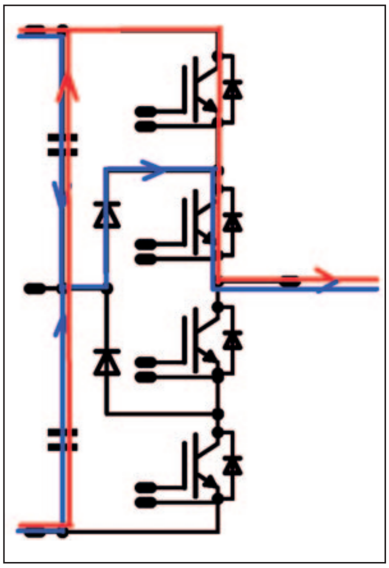


Figure 1: **NCP inverter topology**

DC voltage ripple at NPC inverters

In symmetrical loaded three-phase systems the power is constant.

$P = P_1 + P_2 + P_3$ ($P_{1,2,3}$ = power of the three power lines)

$P_{(t)} = V_{(peak)} * I_{(peak)} * \sin^2(\omega t)$

The lines are shifted with $2\pi/3$.

The total power is:

$P_{tot} = V_{(peak)} * I_{(peak)} * [\sin^2(\omega t) + \sin^2(\omega t+2\pi/3) + \sin^2(\omega t+4\pi/3)] = 1.5 * V_{(peak)} * I_{(peak)} = \text{constant}$

This is also valid for NPC. The problem is that NPC uses a third level which has to be built up by capacitors, and the charge-discharge cycle is only balanced after one sine wave of the grid frequency or 1/3 of a sine wave in the three-phase system. This leads to a ripple with 3x line frequency of usually 150 Hz.

Principle of FC inverters

Compared to NPC inverters, there is no additional external voltage level than DC voltage required, the additional level is generated in the circuit itself. The basic topology is shown in Figure 2. The capacitors are charged in order to provide the voltage for the three levels:

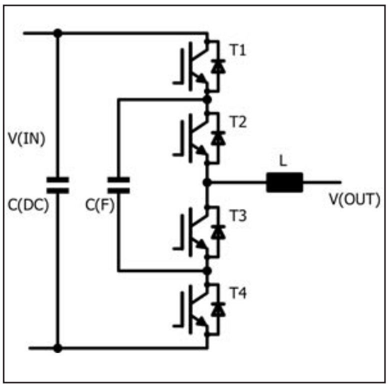


Figure 2: **Topology of 3L FC Inverter**

1. V(DC+): Vdc
2. V(FC): 1/2x Vdc
3. V(DC+): 0 V

In case of 1200 VDC voltage C(F) is charged with 600V C(F1)).

The three levels are: V(DC+) = 1200 V, V(FC) = 600 V, V(DC-) = 0 V. The switching sequence is controlled in a way that the FCs are kept on the same voltage. The capacitor is charged and discharged within the defined voltage limits in the operation.

Excitation in Level 1 and freewheeling in Level 2: During the excitation the upper switches T1, T2 are turned on. For the freewheeling one of the two switches is turned off. For a balanced system the switches are alternating. In every freewheeling cycle a different switch is turned off.

The switching frequency in the switches is only half of the frequency at the inductor. This leads to identical load and losses in all switches. The optimum for all switches regarding static losses and switching losses is the same. This is also valid in reactive power and reverse power direction.

The switching sequence of a 3L FC inverter and charging / discharging status of the FC is shown in Tables 1/2.

Every first freewheeling cycle is charging and every second is discharging the FC. The capacitor is in average at the same voltage. In long term the asymmetry in the circuit might cause an imbalance of the capacitor voltage. The target voltage is 1/2 of the DC voltage.

Here is a simple logic for balancing - the target voltage of the FC is half of the DC voltage:

- If V(FC) < 1/2x V(DC) => charge FC, use Level 2.1 for freewheeling => turn off T2
- If V(FC) > 1/2x V(DC) => discharge FC, use Level 2.2 for freewheeling => turn off T1

It is also possible to use the same PWM

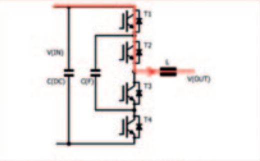
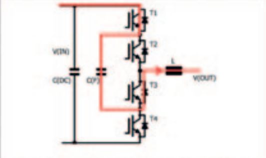
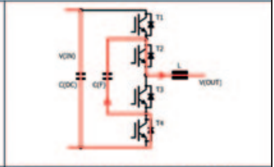
Level 1		Level 2.1		Level 2.2	
Real Power Level 1 / 2					
					
Excitation Level1 (1200V)		Freewheeling Level 2.1 (600V) • Charge C(F)		Freewheeling Level 2.2 (600V) • Discharge C(F)	
T1	T2	T1	T2	T1	T2
ON	ON	ON	OFF	OFF	ON

Table 1: The switching sequence of a 3L FC inverter

	T1	T2	V(OUT)	C(F) (+) charging (-) discharging
Real Power Level 1 / 2: At real power in level 1 are T1, T2 turned on, during freewheeling in level 2 are consecutively T1, T2 turned off				
Level 1	ON	ON	1200V	
Level 2.1	ON	OFF	600V	+
Level 1	ON	ON	1200V	
Level 2.2	OFF	ON	600V	-
Level 1	ON	ON	1200V	

Table 2: Switching sequence of a 3L FC inverter and charging / discharging status of the FC7

sequence as for a standard NPC inverter and just assign the turn-off signal to the right switch according to this logic.

For the balancing the charging status of the FC is required. The following information is needed for a proper controlling of the voltage in the FC:

- V(FC) < 1/2x V(DC)
- V(FC) > 1/2x V(DC)

This is possible without an expensive isolation amplifier. In Figure 3 it is shown that with a voltage divider and a differential amplifier it is possible to compare the voltage of the DC capacitor and the FC, and to provide the data if the voltage in the FC is above or below the target. A simple optocoupler is able to send the information to the microcontroller.

Principle of 4L FC inverters

Here the four-level Flying-capacitors are further discussed. The basic topology is shown in Figure 4.

The capacitors are charged in order to provide the voltage for the four levels:

1. V(DC+): Vdc
2. V(FC1): 2/3x Vdc
3. V(FC2): 1/3x Vdc
4. V(DC-): 0V

In case of 1200V DC voltage, the capacitors are charged with 800 V C(F1) and 400 V C(F2).

The four levels are: V(DC+) = 1200 V, V(FC1) = 800 V, V(FC2) = 400 V, V(DC-) = 0V.

The switching sequence is controlled in a way that the FCs are kept on the same voltage. The capacitors are charged and discharged within the defined voltage limits in the operation.

At real mode, in the positive half-wave there are two different sections of switching, the sinusoidal grid voltage $V_{(t)} > 1/3x$ VDC and $V_{(t)} < 1/3x$ VDC:

1. $V_{(t)} > 1/3x$ VDC:

Excitation in level 1 and freewheeling in level 2. During the excitation the upper switches T1, T2, T3 are turned on. For freewheeling one of the three switches is turned off. For a balanced system in every freewheeling cycle a different switch is turned off.

2. $V(t) < 1/3x$ VDC:

Excitation in Level 2 and freewheeling in Level 3. During the excitation two of the three upper switches are turned on. For freewheeling only one. To avoid additional switching losses we have the additional frame condition to change the switching status only for one switch at one time. The result is that the PWM frequency is reduced to 1/3 per switch, but all three switches are involved (Figures 5/6).

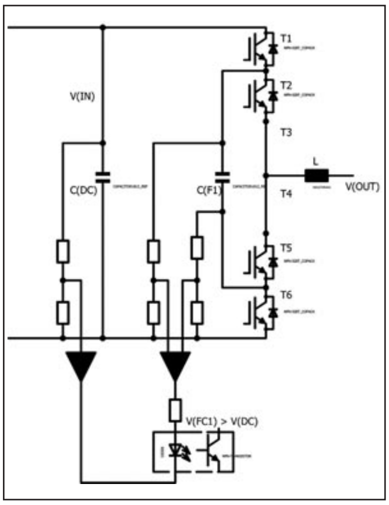


Figure 3: Voltage detection in 3L FC inverter

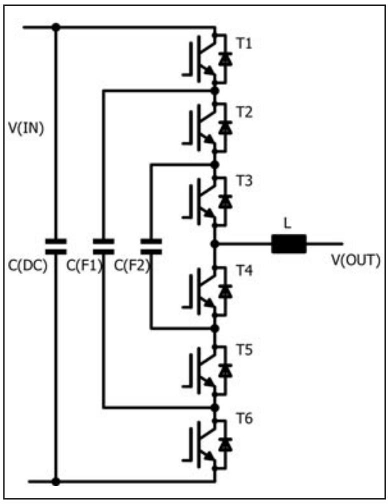


Figure 4: Topology of 4L FC inverter

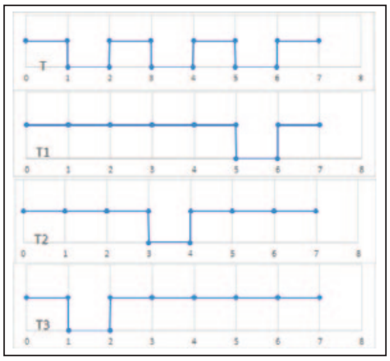


Figure 5: FC gate signal level 1, 2

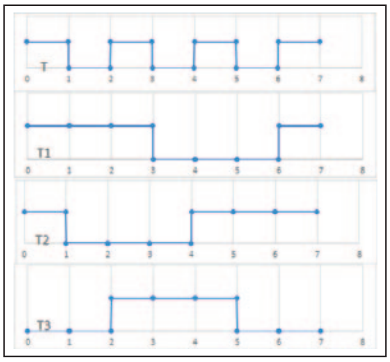


Figure 6: FC gate signal level 2, 3

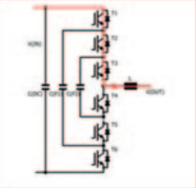
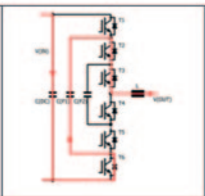
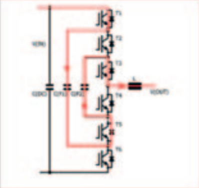
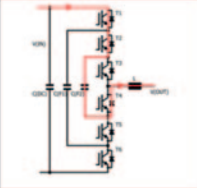
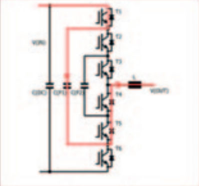
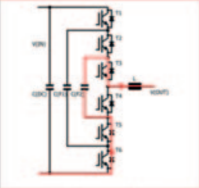
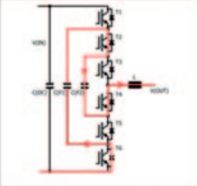
Level 1			Level 2.1			Level 2.2			Level 2.3		
Real Power Level 1 / 2											
											
Level1 (1200V)			Freewheeling Level 2 (800V) • Discharge C(F1)			Freewheeling Level 2 (800V) • Charge C(F1) • Discharge C(F2)			Freewheeling Level 2 (800V) • Charge C(F2)		
T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
ON	ON	ON	OFF	ON	ON	ON	OFF	ON	ON	ON	OFF
			Level 3.1			Level 3.2			Level 3.3		
											
			T1	T2	T3	T1	T2	T3	T1	T2	T3
			ON	OFF	OFF	OFF	OFF	ON	OFF	ON	OFF

Table 3: **Operation of 4L FC inverter at real power**

	T1	T2	T3	V(OUT)	C(F1) (+) charging (-) dis-charging	C(F2) (+) charging (-) dis-charging
Real Power Level 1 / 2: At real power in Level 1: T1, T2, T3 are turned on, during freewheeling in Level 2 consecutively T1, T2, T3 are turned off						
Level 1	ON	ON	ON	1200V		
Level 2.1	OFF	ON	ON	800V	-	
Level 1	ON	ON	ON	1200V		
Level 2.2	ON	OFF	ON	800V	+	-
Level 1	ON	ON	ON	1200V		
Level 2.3	ON	ON	OFF	800V		+
Real Power Level 2 / 3: At real power in Level 2: 2 switches (out of T1, T2, T3) are turned on, during freewheeling in Level 3 remains only one (out of T1, T2, T3) turned on.						
Level 2.3	ON	ON	OFF	800V		+
Level 3.1	ON	OFF	OFF	400V	+	
Level 2.2	ON	OFF	ON	800V	+	-
Level 3.2	OFF	OFF	ON	400V		-
Level 2.1	OFF	ON	ON	800V	-	
Level 3.3	OFF	ON	OFF	400V	-	+

Table 4: **4L FC inverter switching sequence**

The switching frequency in the switches is only one third of the frequency at the inductor. This leads to identical load and losses in all switches. The optimum for all switches regarding static losses and switching losses is the same. This is also valid in reactive power and reverse power direction. Operation at real power (positive half-wave) is shown in Tables 3/4.

In a sequence of three times excitation and freewheeling there are one (Level 1-2 / 4-3) or two (Level 2-3) cycles of charging / discharging the FC capacitors. Charging and discharging of the FC is compensating each other, so that the voltage of the FC will stay within the functional limits (e.g. +/- 10 % of the DC voltage). In the long run the tolerances will lead to some imbalance in the FC´s and have to be compensated.

Here is a simple logic for balancing - the target voltage of the FC is:

V(F1) = 2/3x V(DC); X1 = V(F1)actual / V(F1)target

V(F2) = 1/3x V(DC); X2 = V(F2)actual / V(F2)target

There are the following possible situations:

- X1>1, X2>1 => discharge FC1, FC2
- X1<1, X2>1 => charge FC1, discharge FC2
- X1>1, X2<1 => discharge FC1, charge FC2
- X1<1, X2<1 => charge FC1, FC2

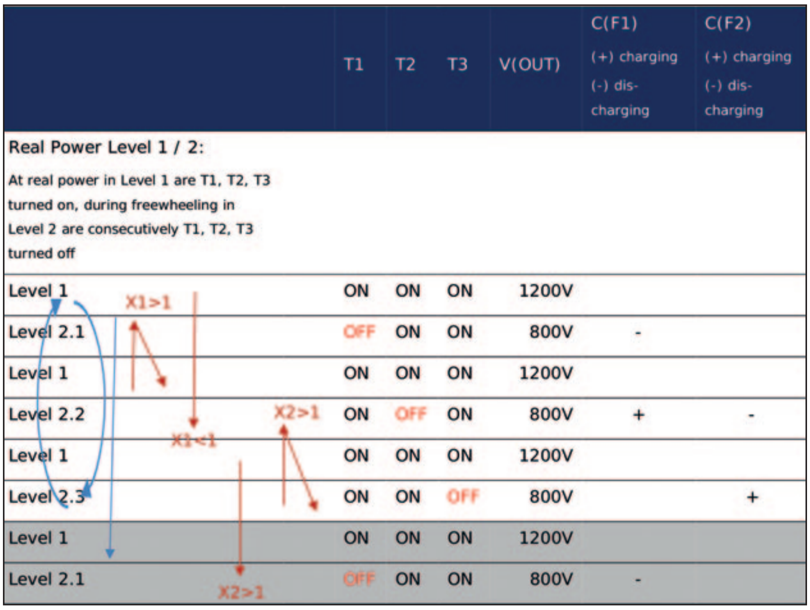
The circuit switches between Level 1 and the three different Level 2 options. During Level 1 it has to be decided which option will be taken - example:

- X1>1 => discharge FC1 (repeat level 1 / level 2.1)
- X1<1 => avoid discharge FC1 (skip level 2.1)
- X2>1 => avoid charge FC2 (skip level 2.3)
- X2<1 => charge FC2 (repeat level 1 / level 2.3)

The balancing at Level 2-3 is more complicated, because there are three different options for Level 2, and three different options for Level 3. Another frame condition is that only one switch is changing its state during one switching cycle. The goal is now to add a charge or discharge cycle for one capacitor without changing the voltage of the second capacitor. This is possible, if a short sequence is repeated where the targeted capacitor is getting the additional cycle (charge or discharge) but the other capacitor is getting the same cycles for both (charge/discharge).

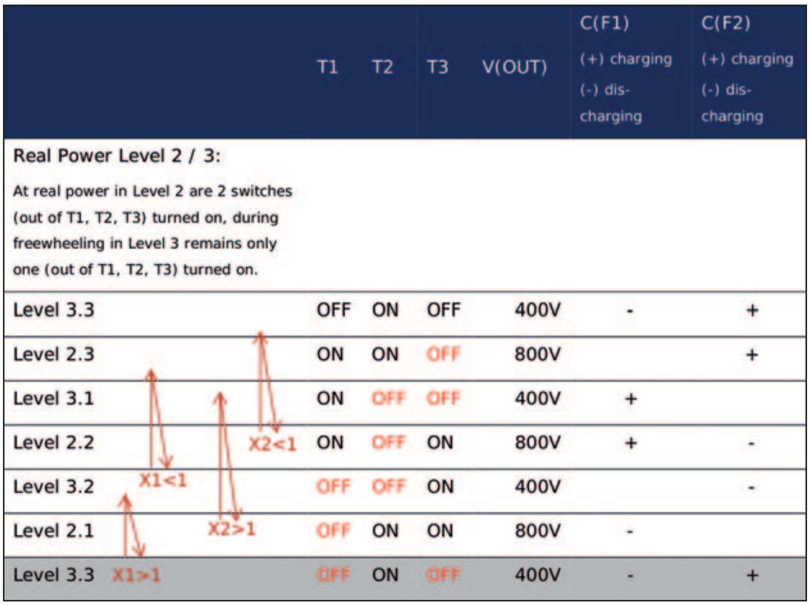
Example:

- X1>1 => discharge FC1 (level 3.3=>2.1=>3.2=>2.1=>3.3…)
- X1<1 => charge FC1 (level 2.2=>3.1=>2.3=>3.1=>2.2…)
- X2>1 => discharge FC2 (level 3.2=>2.2=>3.1=>2.2=>3.2…)
- X2<1 => charge FC2 (level 3.1=>2.3=>3.3=>2.3=>3.1…)



	T1	T2	T3	V(OUT)	C(F1) (+) charging (-) dis-charging	C(F2) (+) charging (-) dis-charging
Real Power Level 1 / 2: At real power in Level 1 are T1, T2, T3 turned on, during freewheeling in Level 2 are consecutively T1, T2, T3 turned off						
Level 1	ON	ON	ON	1200V		
Level 2.1	OFF	ON	ON	800V	-	
Level 1	ON	ON	ON	1200V		
Level 2.2	ON	OFF	ON	800V	+	-
Level 1	ON	ON	ON	1200V		
Level 2.3	ON	ON	OFF	800V		+
Level 1	ON	ON	ON	1200V		
Level 2.1	OFF	ON	ON	800V	-	

Table 5: Levels 1-2.3



	T1	T2	T3	V(OUT)	C(F1) (+) charging (-) dis-charging	C(F2) (+) charging (-) dis-charging
Real Power Level 2 / 3: At real power in Level 2 are 2 switches (out of T1, T2, T3) turned on, during freewheeling in Level 3 remains only one (out of T1, T2, T3) turned on.						
Level 3.3	OFF	ON	OFF	400V	-	+
Level 2.3	ON	ON	OFF	800V		+
Level 3.1	ON	OFF	OFF	400V	+	
Level 2.2	ON	OFF	ON	800V	+	-
Level 3.2	OFF	OFF	ON	400V		-
Level 2.1	OFF	ON	ON	800V	-	
Level 3.3	OFF	ON	OFF	400V	-	+

Table 6: Levels 2.1 – 3.3

It is now possible to change the switching sequence in order to compensate the imbalance with this input. Every switching sequence has the actual condition of X1 and X2 and an expected result after execution of the next switching cycle. If the expected result is not achieved, the cycle will be repeated one time. The signal at the output filter is not affected, it is the same as without the additional balancing sequence (see Tables 5/6).

Voltage measurement in the 4L FC

Analog voltage measurement requires additional effort in isolated measurement. Fortunately, only the ratio between the DC voltages (VFC1= 2/3x VDC and VFC2=1/3x VDC) is required, or if the voltage is fixed, it would be enough to detect if the voltage in the FC is above or below a fixed target voltage.

Figure 7 shows a proposal for a detection of the target voltage ratio.

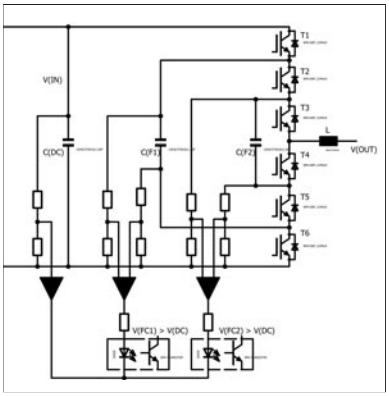


Figure 7: 4L FC inverter, capacitor voltage detection

The FC has to be pre-charged to avoid over-voltage in the switches at the start up. With this circuit (see Figure 8) a simple pre-charging is achieved with a resistor divider circuit. The resistor values have to be calculated as follows:

1. R1.2 = 4x R1.1; R1.1 = R1.3
2. R2.1 = R2.2 = R2.3

The result is: V(F1) = 2/3 * V(DC) and V(F2) = 1/3 * V(DC)

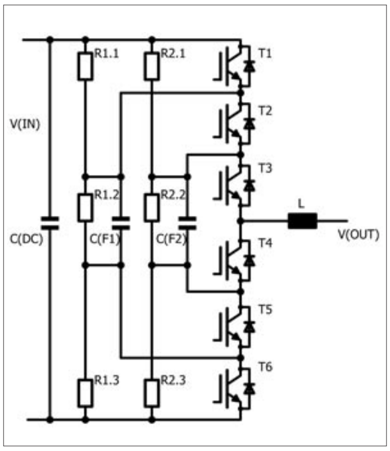


Figure 8: Pre-Charge circuit for FC inverter

Conclusions

The special features of FC inverters are:

* No requirement to provide additional external voltage levels, the switching level
- No presence of low frequency ripple (150 Hz)
- Inductor frequency is 2x (3L) 3x (4L) switching frequency of the individual switches
- All switches are loaded identical during one output sine wave
- The balancing of the FC voltage is possible with low effort in the circuit design and cost (voltage detection and switching sequence)

The utilization of the listed features open opportunities for high efficient FC inverter ideas.

Literature

Thierry Meynard, Henri Foch, "Electronic device for electrical energy conversion between a voltage source and a current source by means of controllable switching cells" US Patent: US5737201A, Apr. 7, 1998

A. Ruderman, B. Reznikov, "Simple Analysis of a Flying Capacitor Converter Voltage Balance Dynamics for DC Modulation" EPE/PEMC 2008, Aachen, Germany

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