UPS systems for power quality solutions

White Paper No.2

SVM Space Vector Modulation

Improved output performance through advanced inverter control

GE Industrial Systems
Via Cantonale, 50
6595 Riazzino, Swizerland
gedeups@indsys.ge.com

www.gedigitalenergy.com

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Contents

Preface

"White Paper" is a collection of documents discussing key advantages of *GE Industrial Systems* UPS systems

These documents are created to support consulting engineers, end-customers, sales force and all others that are looking for more information than available on the standard datasheets.

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Author: Henk Mulder
Department: UPS Product Management
6595 Riazzino (Locarno) – Switzerland

1 Introduction

Over the last decade there have been many innovations in UPS (Uninterruptible Power Supply) technology.

A UPS is basically built up with a rectifier at the input and an inverter at the output (fig 1) The rectifier converts the AC utility voltage into DC voltage. The inverter does exactly the opposite, it converts the DC voltage back into AC voltage to supply the critical load. In case the utility fails or is out of tolerance, the rectifier will be switched off and the batteries will supply the inverter with DC voltage.

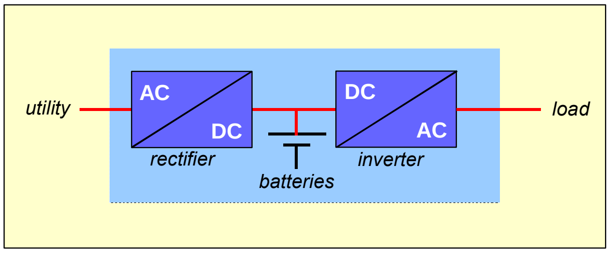

Fig. 1

A UPS is usually supplying a critical load, mostly equipment like computers, mainframes, medical equipment, etc.. Such equipment is sensitive to disturbances on the utility. For example, a dip in the utility voltage can cause hard-disks to crash. Disturbances on the utility can not only damage equipment, but also cause productivity losses and discontinuity in processes. Medical equipment like digital X/ray and CT scanners are pulsating loads, which means that there are significant variations in the current. These loads are switched on and off all the time, within milliseconds. If such equipment is protected with a UPS, the inverter of that UPS should be able to maintain the output voltage wave shape (sine wave) within tolerance, in order to not jeopardize the functionality of the equipment.

Similar performance is required for non-linear loads where the output current is different in shape than the output voltage. Typically computers are equipped with power supplies that act as non-linear loads.

With such requirements, the expectations of the performance of the inverter of the UPS are high. Conventional ways to control the inverter provide good results, but many times the UPS needs to be oversized to maintain the performance. More advanced ways of control are required to prevent this and to make a UPS cost effective.

2 Short description of a three phase inverter

UPS Inverter designs generally use Pulse Width Modulation (PWM) to generate a sine wave out of the DC voltage. In fig. 2 a three phase inverter is represented in a basic diagram:

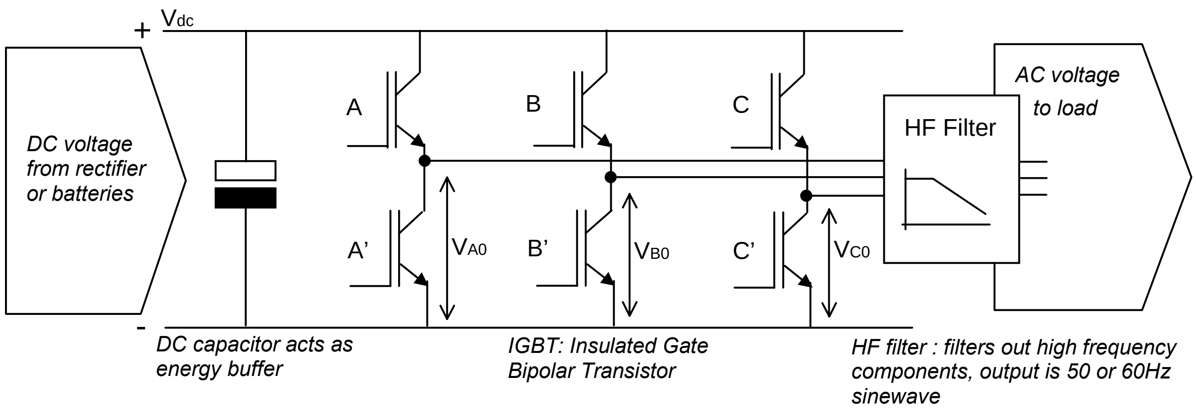

Fig. 2

The rectifier or batteries are supplying DC voltage to the inverter. In between, a large DC capacitor is placed to buffer energy. Typically the DC capacitors are placed in proximity to the IGBTs (Insulated Gate Bipolar Transistors). The IGBTs act as switches. By switching on or off the IGBTs with a high frequency a block wave is generated. This block wave contains the base frequency (50 or 60Hz) and many other higher frequencies. By filtering out the 50 or 60Hz sine wave with a low pass filter the output sine wave is generated at the output.

3 Pulse Width Modulation (PWM)

Pulse Width Modulation is a method, generally used, to define how to switch the IGBTs on and off in a UPS inverter. In case IGBT A is switched on, A' is always switched off and vice versa. In case A is switched on, V_{A0} equals V_{dc}. When A is switched off (and A' is switched on) : V_{A0} equals 0 (zero).

So, by switching, we can generate a block wave (fig. 3) . Typically the frequency of such a block wave is around 5kHz, so the period time is 0.2 ms.

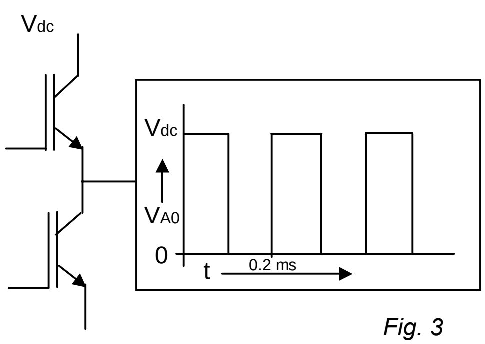

Fig. 3

In case the IGBT A is switched on, $V_{A0} = V_{DC}$. If the IGBT is switched on 50% of the time and switched off the other 50% of the time, the effective value of the voltage: is: (50% * Vdc) + (50% * 0) = ½ Vdc

So by varying the time the IGBT is switched on the effective value of the output voltage can be varied. If we need a 50 or 60Hz output voltage in a sine wave shape we need to vary the switch on/off time , following the wave shape we want at the output. This is called Pulse Width Modulation, PWM

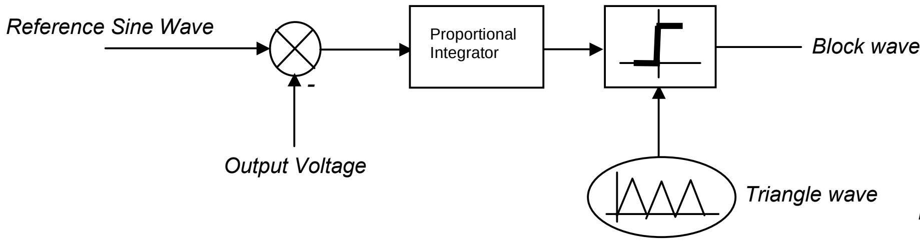

Fig. 4

For the UPS inverter this globally works as follows: A reference sine wave (after deducting the feedback from the output voltage) is amplified and integrated (fig. 4). After that the signal is compared with a generated triangle wave. If the sine wave (output of the integrator) is higher than the triangle the output signal will be ''high'', in the other case ''low''. This provides a block signal with varying width, or duty cycle. (duty cycle = time high / period time) The diagrams in fig 5 and 6 illustrate this. The red wave represents the required output voltage. Fig. 6 shows the first ¼ period. The triangle wave is shown in blue and is compared with the sine wave. The yellow block wave is the result of that comparison and is used to switch on or off the IGBT. As the sine wave is reaching its peak the pulses get wider.

Fig 5 shows the required output voltage. In fig. 6 we see the triangle wave that is compared with the sine wave, for only ¼ period. The result is the yellow block wave. As is clearly visible, the duty cycle of the block wave is varying according to the momentary value of the required output voltage. The result is that the effective value of the block wave is the same as that of the output voltage. Please note that in the diagrams the switching frequency is only 20 times the frequency of the output voltage , 1000Hz in this case. In practical systems with an isolation transformer the switching frequency can be 100 to 150 times the frequency of the output voltage, 5-7.5kHz. At higher frequencies the switching losses in the inverter will increase and other materials need to be applied in inductors. So in a typical UPS inverter the IGBTs are switched on and off with a frequency of around 5kHz, with a varying duty cycle.

The last step is to filter out the high frequency of the block wave to obtain a sine wave of 50 Hz. (HF filter in fig 2)

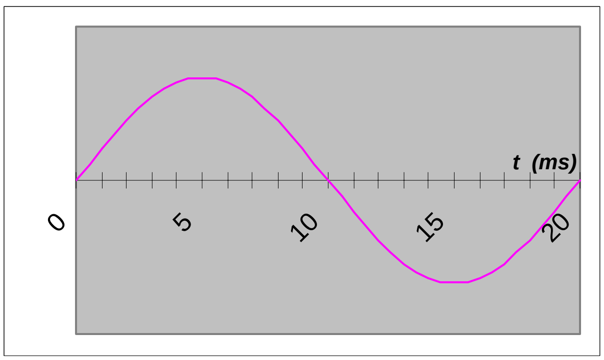

Fig. 5

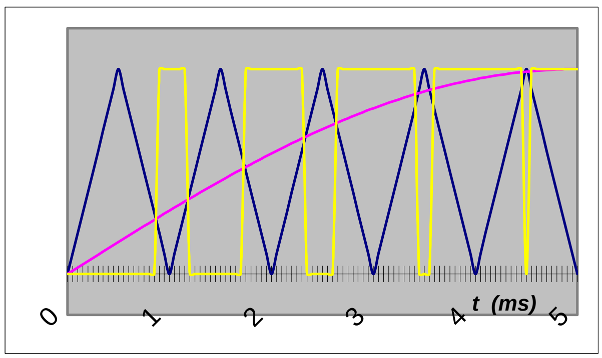

Fig. 6

4 Space Vector Modulation

PWM, as discussed in paragraph 4, can be generated by analogue or digital control electronics. The advantages of digital controls over analogue are:

- Stability (no drift, offsets or aging effects)
- Precision (noise immunity)
- Flexibility (can be customized by changing software)

Even if done digitally, significant computing time is required, as the PWM signals have to be calculated in real time. By using Space Vector Modulation this calculation process is simplified. As it is simplified, less computing time is required, and therefore better performance can be obtained.

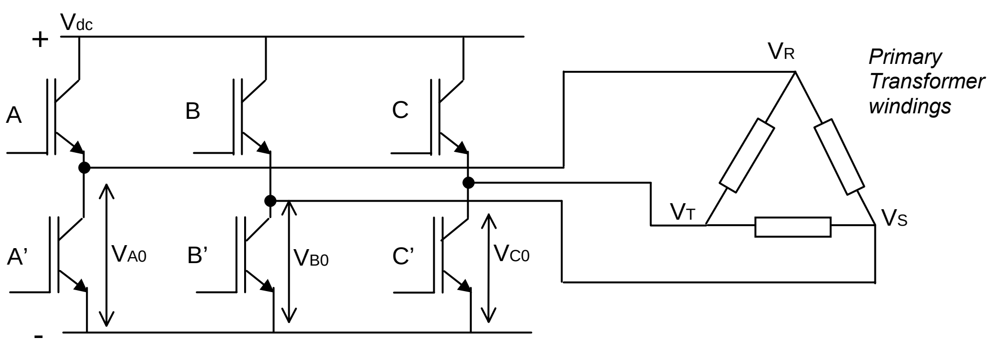

Fig. 7

As we have 3 switches (A, B and C) there are 8 different switching combinations. For example A on, B off, C on.

We can analyse for all switching combinations the phase-phase voltages on the primary winding of the transformer. If we look to the voltages that need to be generated between each leg (fig 8) we can split that into 8 different ''spaces'', S_1, S_2 etc. For each space we can use the table to define which switching states the inverter must use to obtain those voltages. For example for period (''space'') S_1, we see that the V_{RS} is positive, V_{ST} is negative and V_{TR} is positive. Besides the fact that these voltages are positive or negative they also reach a point where they are zero. From the table it can be read that in period S_1 the inverter needs to be switching between state Nr. 1, 2, 8 and 6.

Nr	A	B	C	V_{A0}	V_{B0}	V_{C0}	V_{RS}	V_{ST}	V_{TR}	S_1	S_2	S_3	S_4	S_5	S_6
1	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X
2	0	0	1	0	0	V_{dc}	0	$-V_{dc}$	V_{dc}	X					X
3	0	1	0	0	V_{dc}	0	$-V_{dc}$	V_{dc}	0				X	X	
4	0	1	1	0	V_{dc}	V_{dc}	$-V_{dc}$	0	V_{dc}					X	X
5	1	0	0	V_{dc}	0	0	V_{dc}	0	$-V_{dc}$		X	X			
6	1	0	1	V_{dc}	0	V_{dc}	V_{dc}	$-V_{dc}$	0	X	X				
7	1	1	0	V_{dc}	V_{dc}	0	0	V_{dc}	$-V_{dc}$			X	X		
8	1	1	1	V_{dc}	V_{dc}	V_{dc}	0	0	0	X	X	X	X	X	X

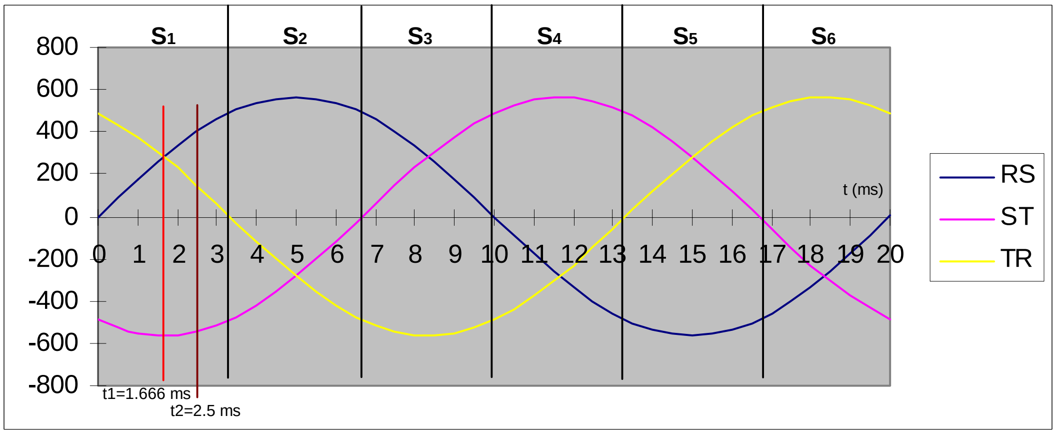

Fig. 8

Fig 8 in combination with the table can also be represented in a hexagon, as shown in fig 9

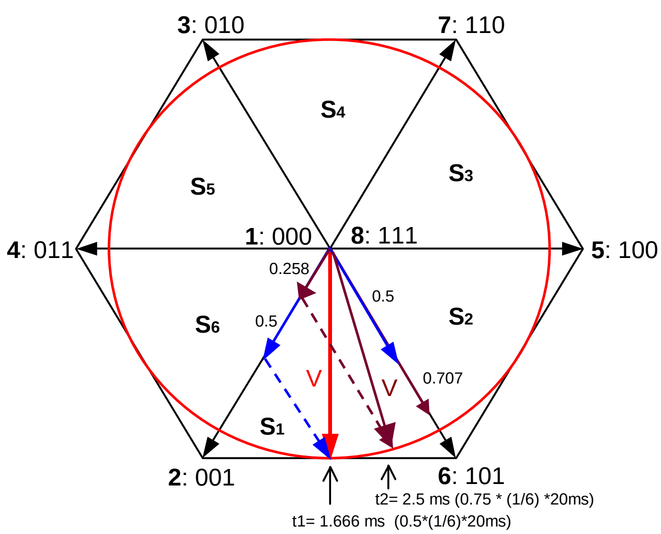

Fig. 9

In period S_1 the inverter will switch between switching states 1,2, 8 and 6, in the period S_2 between: 1, 6, 8 and 5. etc.

One full period (in case of 50Hz 1 period is 20ms) can be represented by a vector V making one full circle in the hexagon. The period showed in figure 8 starts in the hexagon at state 2 and is then turning counter clockwise.

As shown in fig 9 at t_1=1.666 ms the vector V (red) is built up by staying 25% of the time in state 1, 25% of the time in state 2, 25% of the time in state 8 and 25% of the time in state 6. This switching pattern in one period of the switching frequency is shown in figure 10.

For t_2= 2.5 ms the required time per switching state is calculated as follows:

$V_{RS} = \sin(2.\pi.f.t)$ at t=2.5ms V_{RS} = 0.707 (73.2% of 0.965 which is the total)
$V_{TR} = \sin(2.\pi.f.t - 4/3.\pi)$ at t=2.5ms V_{TR} = 0.258 (26.8% of 0.965 which is the total)

Please note that V_{RS} and V_{TR} are normalized to 1 where 1 corresponds with 565V, the maximum value (400√2)*

So within one switching period the inverter needs to stay

	25.0% of the time on state 1 (always)
*26.8% * 50% =*	*13.4% of the time on state 2*
	25.0% of the time on state 8 (always)
*73.2% * 50% =*	*36.6% of the time on state 6*

Fig 10 shows the switching states as shown at t_1 in fig 9 and visualizes the switching states of leg A,B and C during 1 period. (1 period is 200 microseconds, as the switching frequency is 5kHz).

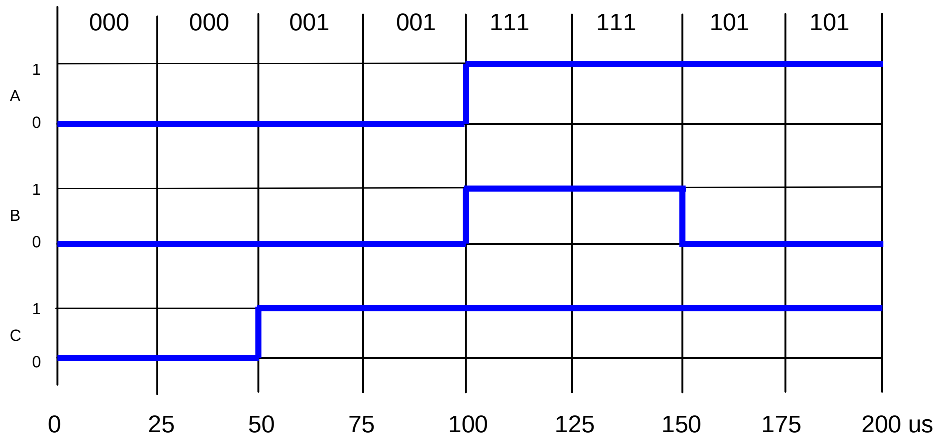

Fig. 10

In a UPS Space Vector Modulation can be implemented by means of DSPs (Digital Signal Processors). These are microprocessors which are suitable to process analogue signals. DSPs provide fast sampling rates which make them ideally suited to UPS control.

By using an isolation transformer on the output of the inverter, special modulation techniques can be applied. The modulation index can be increased with 15% by adding a 3^{rd} harmonic (150Hz in case of 50Hz output) to the signal on each leg of the transformer. As the transformer is in dy configuration, this 3^{rd} harmonic will not appear on the output voltage. This optimisation is not possible in transformerless inverters (UPS).

5 Benefits

Space Vector Modulation for a three phase UPS inverter makes it possible to adapt the switching behaviour to different situations such as: half load, full load, linear load, non-linear load, static load, pulsating load, etc. In combination with a zig-zag three phase transformer in the output this provides the following advantages:

- Very low values can be reached for the output voltage THD (<2% for linear loads., <3% for non linear loads)
- Robust dynamic response (<3% deviation at 100% load step, recovery time to <1%: <20ms)
- The efficiency of the inverter can be optimized, for each load condition.
- Because of the strong regulation in combination with a zig-zag transformer the inverter can accept a 100% unbalanced load and maintain the performance
- SVM enables more efficient use of the DC voltage (15% more than conventional PWM techniques, so the inverter will accept a 15% lower DC voltage making full use of the available battery energy)
- By applying special modulation techniques the peak currents in the IGBTs can be reduced compared to similar inverters. This improves the MTBF of the inverter, since there is less thermal stress on the IGBT chip.
- By changing the switching behaviour of the inverter, the audible noise can also be influenced and therefore be minimized.

Space Vector Modulation provides excellent output performance, optimized efficiency, and high reliability compared to similar inverters with conventional Pulse Width Modulation.