IMPLEMENTATION AND DESIGN OF A CASCADE MULTILEVEL INVERTER

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***Abstract*— A cascade bidirectional multilevel inverter is designed and implemented with two different transistor technologies; to determine which technology is the best for implementing this type of converts in our territory (Colombia). Based on this, THD, power efficiency and size are measured.**

***Index Terms*—Full Bridge, THD, Mosfet, GaN, Si, lithium batteries, SIMULINK.**

I.INTRODUCTION

There is a lately furor of solar energy generation due to the high energy demand and the environmental impact of typical fossil fuel generators [1]. In isolated areas where the distribution network would not reach, these energy systems become the most necessary. However, this type of generation is typically implemented with solar panels in DC, so the implementation of a DC/AC converter is necessary because the consumption is normally done in AC; and in many cases bidirectional because the energy storage is done in DC. In addition, this converter helps the energy management by charging batteries during periods of time where the consumption is minimum and feeding the line when the consumption is higher.

This need leads to the investigation of new converters topologies and new technologies for their implementation, which improve their efficiency, costs, and size.

I.I Converter topology

An H-Bridge(HB) inverter is a converter whose main function is to convert DC energy to AC [2] for supplying energy for household appliances or to inject current into the distribution grid. To achieve this function, two types of topologies are typically implemented; The first is a boost inverter, which allows being fed with a low voltage battery and the second is a single inverter, but with a high voltage input. To implement these converters with batteries at low voltage two drawbacks are presented, the first, referring to the first topology, is that having boost converters the current values in the input batteries are higher, increasing losses [3]; the second, the series connection of low voltage batteries to obtain a high input voltage, needs a series of external circuits to be able to regulate its voltage and current in charging states. However, there is a topology that can avoid the implementation of an elevator converter and allows the use of several batteries at low voltage, this converter is known as multilevel inverter [4], implemented by connecting several inverters at low voltage connecting their outputs in series, to obtain greater voltage at the circuit output. In addition, these inverters eliminate harmonics by adding the output signals of several simple inverters, Fig 1 [5].

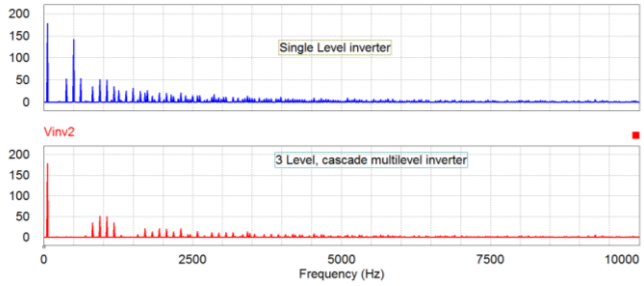

Fig 1 THD, left common inverter, right multilevel inverter

There are several types of HB multilevel inverters, each of them with different characteristics in terms of harmonics reduction and output levels.In table 1 [6], Some HB inverter are compared.

Multilevel Inverter	Levels(#)	Maximum amplitude
CEMI	$2h+1$	hE
QLMI	$2*(3^{h-2})+1$	$3^{h-1}E$
BHMI	$2^{n+1}-1$	$(2^h-1)E$
THMI	3^h	$\frac{3^h-1}{2}E$

Table 1 Comparative analysis of multilevel HB Inverters

According to this, the inverter with a greater amount of levels is the THMI, however, it requires different types of input voltages (Series interconnection of batteries). The inverter which reduces the interconnection of batteries is the CEMI, as all the input voltages have the same magnitude [6]; thus, this converter is the best choice for this dissertation, as the research project is based on energy consumption without the interconnection of batteries.

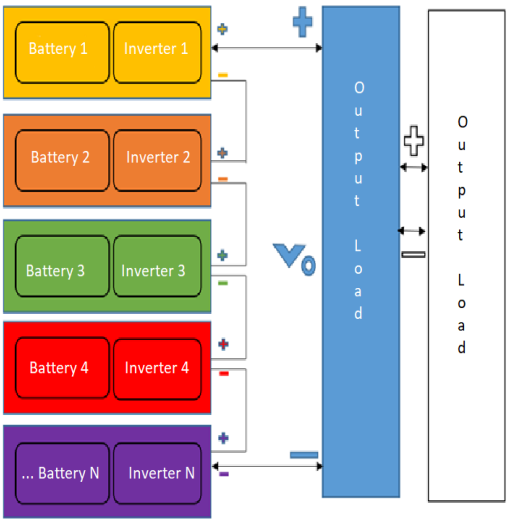

Fig 2 implemented circuit block diagram

II. SPECIFICATIONS

The inverter must be powered by at least 4 lithium-ion batteries, each of 48V 25AH and have an output equal to 120 Vrms, it must deliver an average power of 1000 W to a resistive charge, each battery must supply an average power of 250 W.

III. IMPLEMENTATION AND DESIGN

Unipolar Modulation, there are 4 possible states of commutation: When $S_1 = S_2 = 1, S_1 = S_2 = 0, S_1 = \overline{S_2} = 0$ and $S_1 = \overline{S_2} = 1$

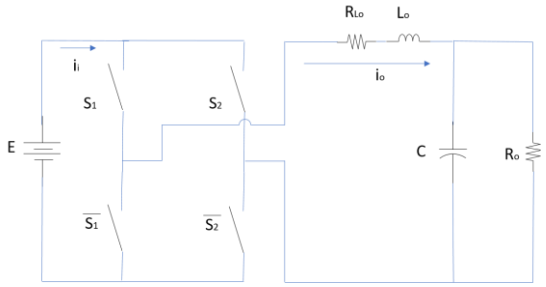

Fig 3 Schematic of single level, without input filter for modeling

(S_1, S_2)	State variable equations
(1,1)	$\left[L_o \frac{di_o}{dt} = E - [2R_{DS_{on}} + R_{L_o} i_l + v_o]\right]$ $[i_c = i_l - i_o]$
(1,0)	$\left[L_o \frac{di_o}{dt} = -[2R_{DS_{on}} + R_{L_o} i_l + v_o]\right]$ $[i_c = i_l - i_o]$
(0,1)	$\left[L_o \frac{di_o}{dt} = -[2R_{DS_{on}} + R_{L_o} i_l + v_o]\right]$ $[i_c = i_l - i_o]$
(0,0)	$\left[L_o \frac{di_o}{dt} = -E - [2R_{DS_{on}} + R_{L_o} i_l + v_o]\right]$ $[i_c = i_l - i_o]$

Table 1 Model result of circuit in Fig 3

By finding the volt-second balance in the inductor and the charge balance on the output capacitance the transfer function is:

$$EU - V_p - R_x \frac{V_p}{R_o} = 0 \qquad (1)$$

According to equation, the modulation index is $U = 0{,}934$ with $E = 48V; V_p = 42{,}5\ V; R_x = 0{,}208\Omega; R_o = 3{,}6\ \Omega$.

IV. SIMULATION

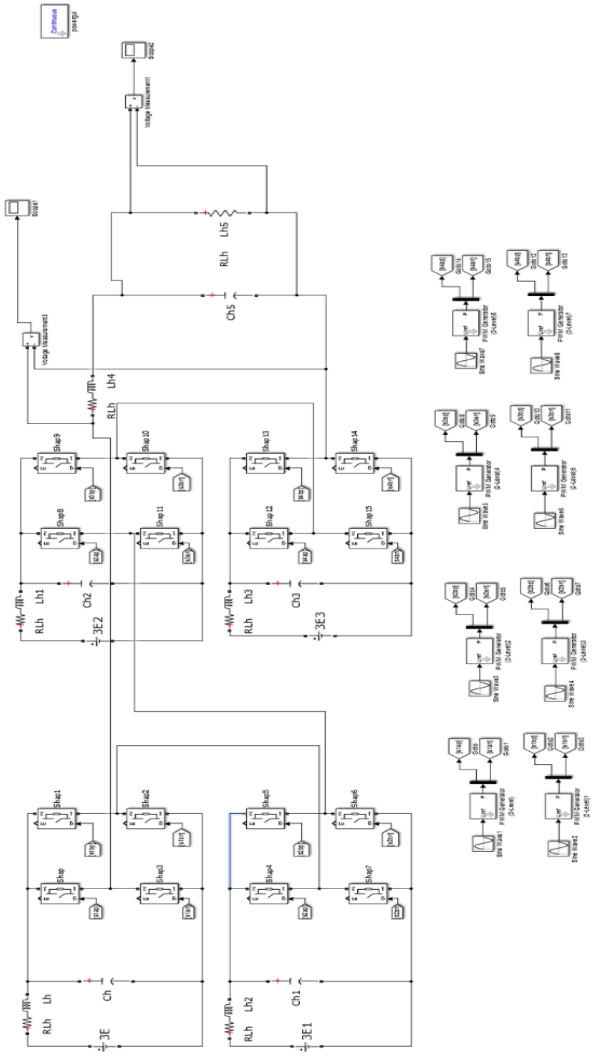

Fig IV Isolated Cascade multilevel inverter

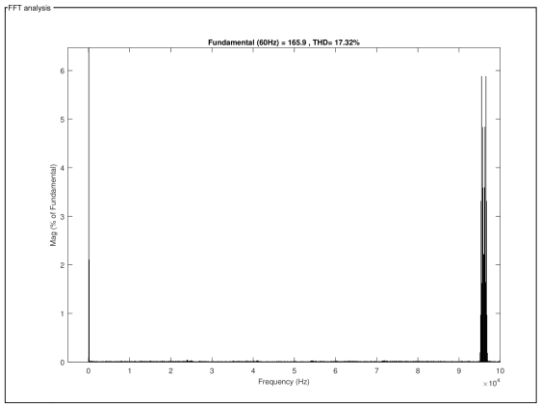

Fig 5 Cascade multilevel inverter spectre before the output filter.

Fig 5 shows a THD of 17.32% before the output filter.

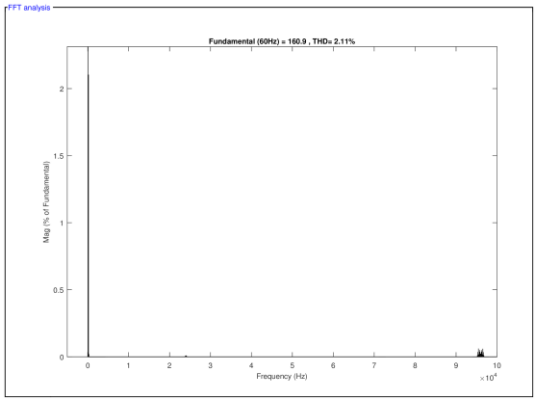

Fig 6 THD after the output filter.

Fig 6 shows a THD of 2.1% after the output filter. The output power simulated is P= 917.3 W.

V. RESULTS

As the worst scenario for power dissipation is 4 levels working each one to handle 250W, those levels where implemented to design the output filter a material 77 ferrite is used and a AC ceramic capacitor. As the working frequency of these elements is around the 100kHz, the output filter was designed to filter a decade before as mentioned in the section before.

As the switching frequency of each half bridge is the output frequency divided by the number of half bridges the multilevel inverter is formed, each MOSFET is implemented at a frequency of 12kHz, this to operate at maximum power; however, to test the GaN technology against the silicon traditional ones, the frequency is pitched up to determine the performance this test is done at lower power than the nominal one.

A. *GaN Results*

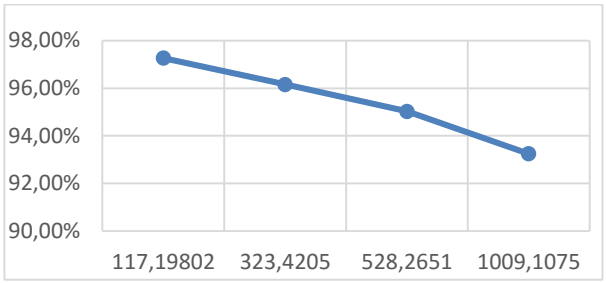

Fig 7 efficiency GaN 12kHz. Efficiency vs Power [W]

As Fig 7 shows, the GaN technology has an efficiency around the 93% calculated by measuring average input and output power of the whole converter. when the input power is near the 1kW. The power the batteries where supplying the power shows in tables 3

	Current [A]	Voltage [V]	Power [W]
Bat1	5.17	48.23	249.34
Bat2	5.16	48.97	252.68
Bat3	5.16	49.02	252.94
Bat4	5.16	49.25	254.13

Table 3 input power batteries 1kW GaN

	Current[A]	Voltage[V]	Power[W]
Bat1	2.7	48.57	131.139
Bat2	2.69	49.29	132.5901
Bat3	2.7	48.56	131.112
Bat4	2.69	49.6	133.424

Table 4 input power batteries 500W GaN

	Current[A]	Voltage[V]	Power[W]
Bat1	1.65	48.81	80.5365
Bat2	1.64	49.51	81.1964
Bat3	1.64	48.8	80.032
Bat4	1.64	49.79	81.6556

Table 5 input power batteries 300W GaN

	Current[A]	Voltage[V]	Power[W]
Bat1	0.593	49.04	29.08072
Bat2	0.593	49.71	29.47803
Bat3	0.593	49.03	29.07479
Bat4	0.592	49.94	29.56448

Table V input power batteries 100W GaN

Fig 8 shows when the output frequency is pitched up to 480kHz (60kHz on each HB), to determine how the efficiency of the converter is decreased, this in order to be compared with silicon.

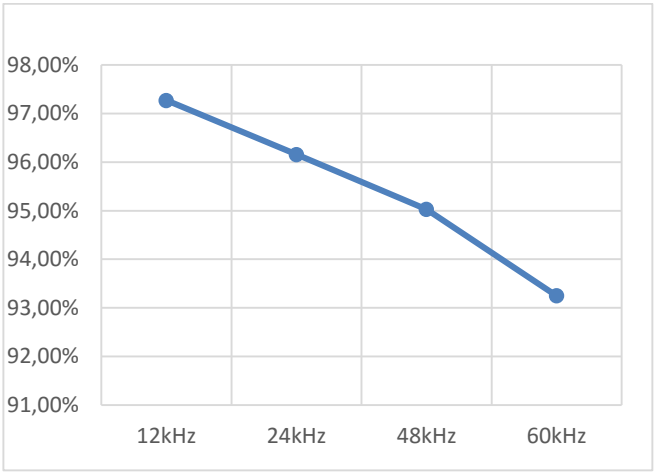

Fig 8 efficiency GaN pitching up the frequency at 100W, Efficiency vs Frequency

Also, the THD is measured at maximum power, with and without output filter.

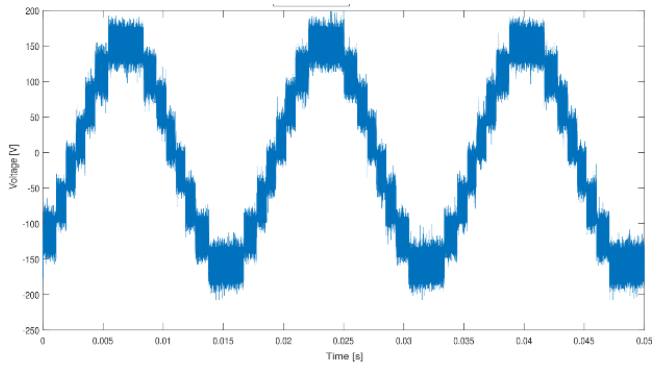

Fig 9 Output Voltage NonFilter GaN 1kW output power.

Fig 9 shows the output voltage without filter at 1 kW of output power. The RMS voltage at these conditions is 114.2 V. The THD measured is 17.1 %.

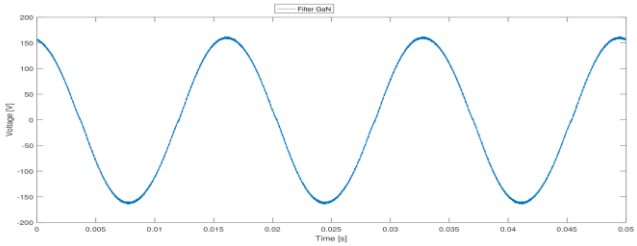

Fig 10 Output Voltage Filter GaN 1kW output power.

Fig 10 shows the output voltage without filter at 1 kW of output power. The RMS voltage at these conditions is 114.2 V. The THD measured is 1.65 %.

B. Silicon results

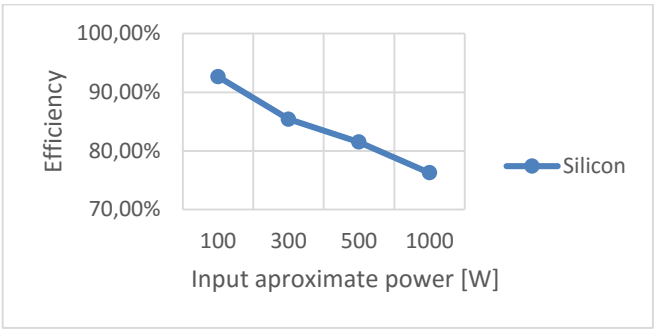

Fig 11 Efficiency power shift to 1kW silicon

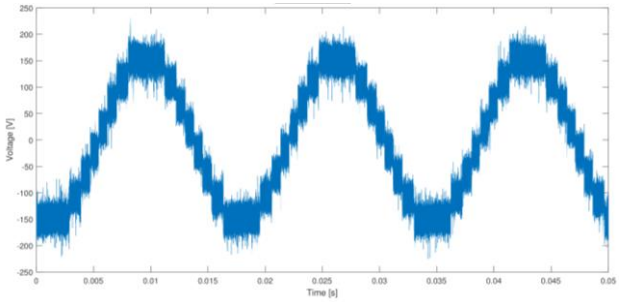

Fig 12 Output Voltage NonFilter Silicon 1kW output power.

Fig 12 shows the output voltage without filter at 1 kW of output power. The RMS voltage at these conditions is 113.89 V. The THD measured is 16.83 %.

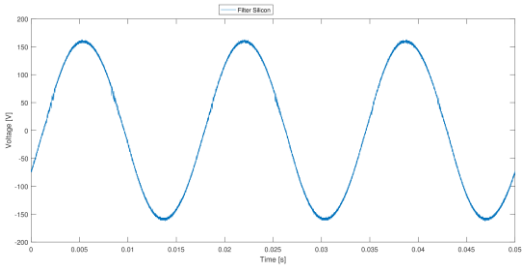

Fig 13 Output Voltage Filter Silicon 1kW output power.

Fig 13 shows the output voltage without filter at 1 kW of output power. The RMS voltage at these conditions is 114.2 V. The THD measured is 1.71 %

C. Regulation of the state of charge of batteries in Rectifier and Inverter operation

According to the overall aim, the inverter must be capable of being bidirectional and regulate the charge state of the batteries. To prove this operation to help the research project some test open-loop where tested with the GaN technology. Only one level of the inverter is implemented.

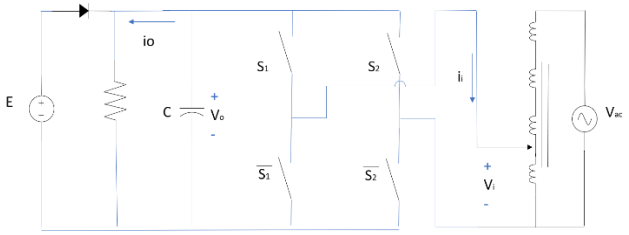

Fig 14 Schematic of the circuit for bidirectional testing.

D. Rectifier operation

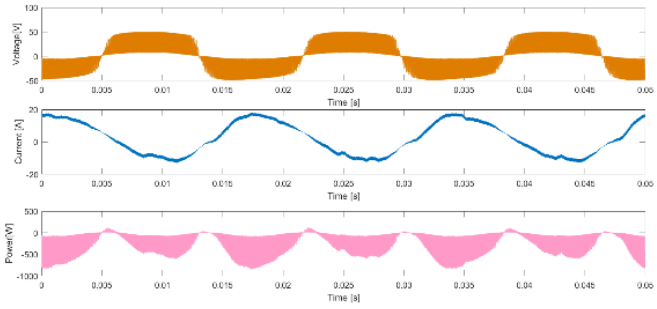

Fig 15 Orange Vi(up), Blue Ii(mid), Pink Pi=Vi*Ii(bottom)

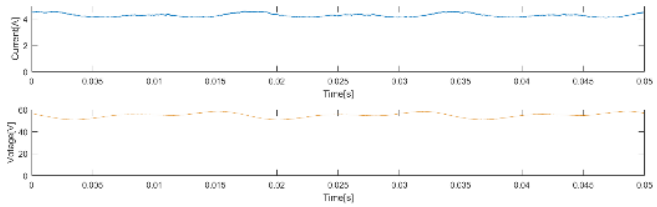

Fig 16 Blue Io(up), Orange Vo(bottom)

Also, the complete inverter was tested as a rectifier. For the implementation of the circuit, an inductor in series with the variac is installed.

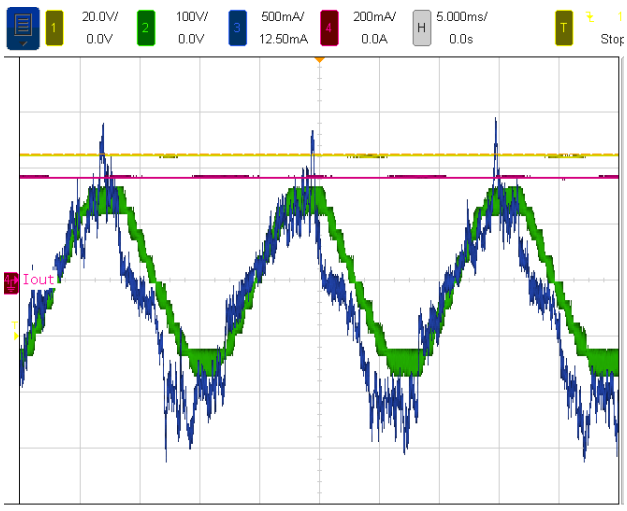

Fig 17 Yellow Vo, Pink Io, Green Vi, Blue -Ii.

E. Regulation state of charge and discharge.

Fig 6-12 Shows in pink the voltage sensed in the output of a variac, the inverter is connected to the power grid as a rectifier, in yellow and in green two DC output voltages, to simulate the regulation the modulation index of one output voltage is lowered, to compensate this changing the rest of the outputs are changed in the same proportion. It is noticed that the input sinusoidal voltage does not changes during the transition.

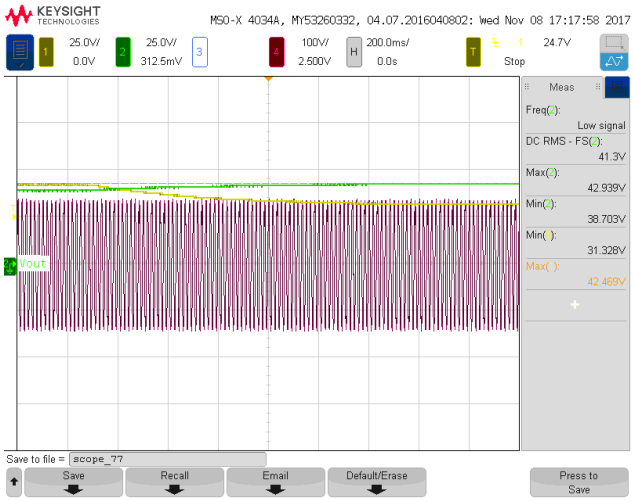

Fig 18 Regulation state of charge

This index modulation is done using the inverter as an isolated inverter to simulate a regulation of the state of discharge of batteries. As shown in Fig 18. In this Fig is noticed too that the output voltage of the converter does not change during the transition. In this Fig, the pink and the blue signals are two currents of two different batteries.

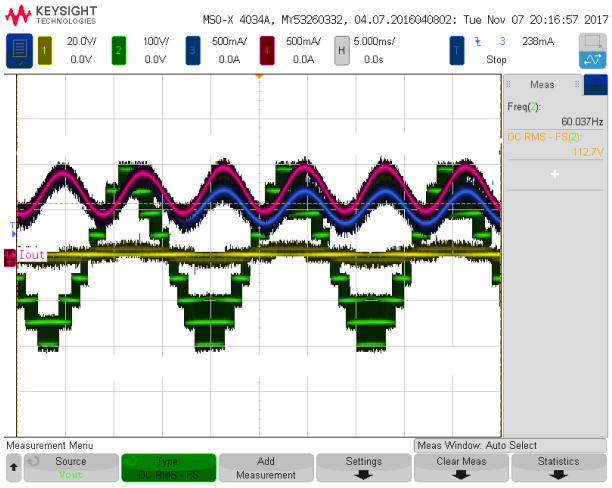

Fig 19 Regulation state of discharge

VI. CONCLUSIONS:

1) As it was expected, the efficiency of the silicon converter decreased when the switching frequency was pitched up, as the material 77 does not handles frequency over 100kHz, these high frequencies where tested without the output filter.
2) When the state of discharge of the batteries is changed, despite the RMS voltage of the output signal does not change it is noticed that the 9 levels that were supposed to have the cascade multilevel inverter changes in their form.

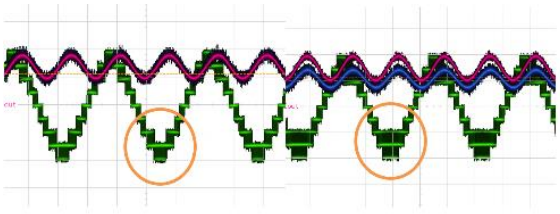

Fig 20 Change in the output voltage due to modulation index changing.

This effect is produced because the modulation index is changed without closing the control loop, as the voltage and current of the battery is not sensed, the converter is incapable of regulating the modulation to keep the levels shaped in the output of the converter. It should be clarified that the aim of this dissertation is not to control the converter, for this reason, this test is just an advance made to the future assignments of this research project.

3) Table 7-1 Shows in green the lowest value of the 3 implemented PCB, in yellow the middle value and in red the highest of them. It is noticed that in terms of size the GaN FETs (first and second rows) are clearly better. However, the EPC GaN FET has the need of a more expensive PCB and was not possible to implemented at the maximum power. With the GaNsystems fet implemented it is possible to fabricate PCBs at the same price of a silicon fet, they can be pitched up its frequency to reduce the size and price of the output filter and they cost per unit 2 times more than a silicon transistor of the same electrical specifications

	GaN	Silicon
Price Device	5,64 USD Single-FET	1,93 USD Half-Bridge
Price PCB	80 USD (16 Full bridge)	80 USD (Full bridge)
Size, Volume	10,3 mm^3	380 mm^3
PCB size	12 cm^2 (Not heat sink needed)	12 cm^2 (Taller heat-sink)

Table 11 Comparison

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