A 90kVA / 400Hz Inverter for Ground Support for Aircrafts

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Abstract – An inverter applied as a power supply for aircrafts is proposed in this paper. This inverter has a regulated rms output voltage and low harmonic distortion. A special transformers' connection is used to reduce the harmonic distortion spectrum. The operating principles, theoretical analysis, relevant equations and simulation results are presented in this paper.

I. INTRODUCTION

This paper presents the conception, simplified analysis and simulation of a 90kVA three-phase isolated inverter applied as a ground support power supply for aircrafts.

The rms output voltage is controlled by a special modulation of the drive voltages that adapt themselves to the input voltage variations.

In order to reduce the sizes of the inductors and capacitors sizes of the output filter since the required operation frequency is 400Hz, which is the standard system for commercial aviation, a special connection for transformers was chosen to eliminate harmonics. Using this strategy, the lowest order harmonic generated by the inverter is theoretically equal to 11 times the fundamental frequency.

II. THE CIRCUIT AND OPERATION PRINCIPLE

A. Circuit Description

Two three-phase inverters and two transformers connected in Delta-Wye and Delta-Zig-Zag, respectively, compose this power supply. Each inverter supplies the primary side of one transformer and their secondary sides are series connected as shown in Fig. 1. The inverter that supplies the Delta-Zig-Zag transformer has a -30 degree phase shift in relation to the other inverter.

B. Principle of Harmonics Elimination

With today's increased use of modern electronics has come a corresponding concern about harmonics and their effects on the power system. Harmonics are undesirable in any electrical system because they reduce the power factor, distort the current and voltage waveforms and causes electromagnetic interference.

An effective way to reduce harmonics is by using a special connection for transformers to cancel certain harmonics.

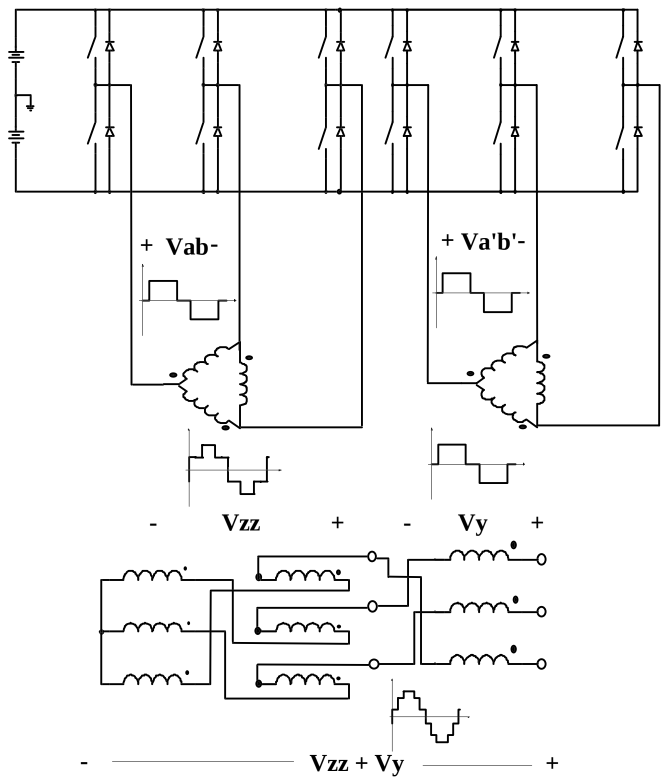


Fig. 1 – Power Stage Diagram of the Proposed Inverter.

In Fig. 1 the secondary voltage, Vy, is proportional to a harmonic series as represented by (1).

$$Vy(wt) \propto \frac{2\sqrt{3}}{\pi}\left(\cos(wt)+\frac{\cos(5wt)}{5}-\frac{\cos(7wt)}{7}-\frac{\cos(11wt)}{11}\cdots\right) \quad (1)$$

The secondary voltage, Vzz, is also proportional to a harmonic series as shown by (2).

$$Vzz(wt) \propto \frac{2\sqrt{3}}{\pi}\left(\cos(wt)-\frac{\cos(5wt)}{5}+\frac{\cos(7wt)}{7}-\frac{\cos(11wt)}{11}\cdots\right) \quad (2)$$

The total secondary voltage that will be supplied to the load is equal to the addition of voltages Vy and Vzz. Therefore the total voltage Vy + Vzz will be proportional to the addition of (1) and (2) and is represented by (3).

$$Vy + Vzz(wt) \propto \frac{2\sqrt{3}}{\pi}\cdot\left(2\cos(wt) - \frac{2\cos(11wt)}{11}\cdots\right) \quad (3)$$

By way of (1) and (2) it can be concluded that the Wye and Zig-Zag windings are two similar harmonic sources and their connection cancels the 5^{th} e 7^{th} harmonics. This conclusion is proved by (3).

III. THEORETICAL ANALYSIS

A. Modulation principle

Given a non-modulated voltage waveform, Vx, as shown in Fig. 2(a), the peak value of voltage Vx at the fundamental frequency can be calculated by way of (4).

$$V_1x = \frac{4}{\pi}\cdot Vcc_1 \quad (4)$$

In order to control the rms value of fundamental component of voltage Vx, it is necessary to add to Vx a modulated voltage, Vy, that is shown in Fig. 2(b). The peak value of the fundamental voltage component is defined by (5).

$$V_1y = -\frac{4\cdot(2\cdot Vcc_1)}{\pi}\cdot\cos\left(\frac{\pi-\Delta\theta}{2}\right) \quad (5)$$

By adding voltages Vx and Vy, the modulated voltage, Vxy, shown in Fig. 2(c), can be obtained. Vxy will control the rms value of the fundamental voltage component. Therefore, the magnitude of the fundamental component of modulated voltage Vxy is given by (6).

$$V_1xy = \frac{4}{\pi}\cdot Vcc_1\left(1 - 2\cos\left(\frac{\pi-\Delta\theta}{2}\right)\right) \quad (6)$$

Defining $F(\Delta\theta)$ as a function of $\Delta\theta$, the voltage magnitude can be defined by (8).

$$F(\Delta\theta) = 1 - 2\cos\left(\frac{\pi-\Delta\theta}{2}\right) \quad (7)$$

$$V_1xy = \frac{4}{\pi}\cdot Vcc_1\cdot F(\Delta\theta) \quad (8)$$

In a three-phase system, the non-modulated line voltage, Vab, has the shape presented in Fig. 3(b). Applying the modulation principle to a three-phase system, the rms value of the modulated line voltage at the fundamental frequency is defined by (9).

$$Vab_{rms} = 1.56\cdot Vcc_1\cdot F(\Delta\theta) \quad (9)$$

Vcc1 corresponds to half of the DC bus voltage Vcc supplied to the inverter by the input stage. The input stage is formed by a full-wave three-phase rectifier with a LC filter at the output. Therefore, voltage Vcc is given by (10).

$$Vcc = 1.35\cdot Vin \quad (10)$$

Vin is the rms input line voltage.

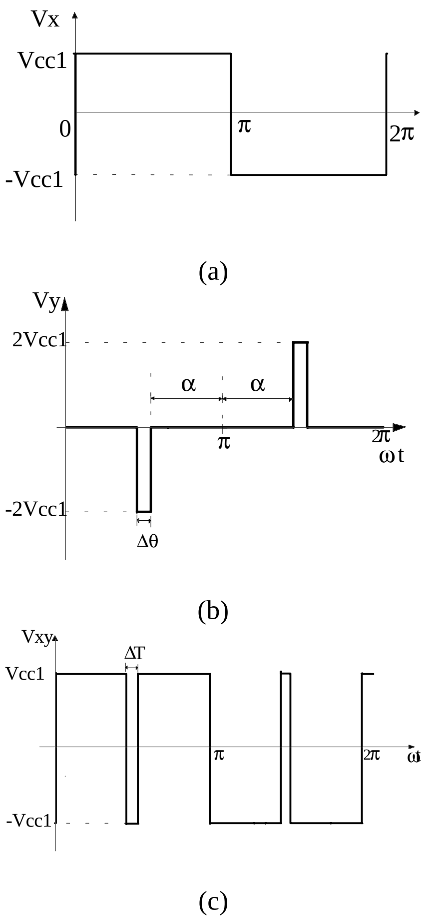


Fig. 2 – Waveforms related to the modulation.

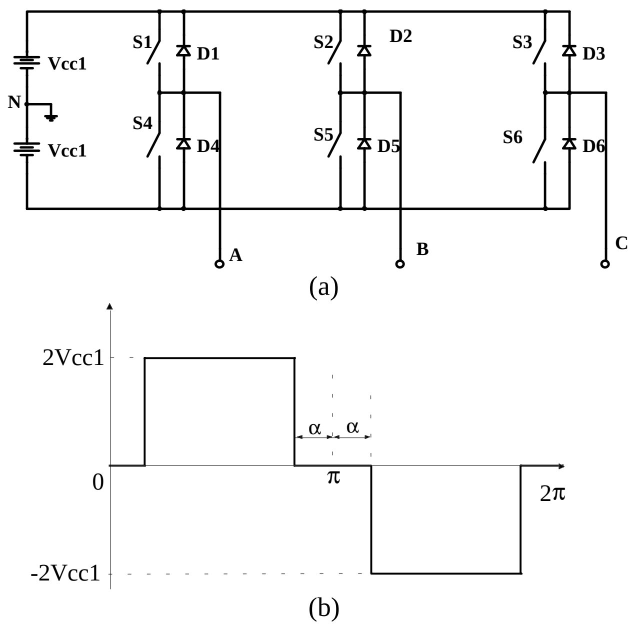


Fig. 3 – Three-Phase Inverter and line voltage waveform.

The average value of voltage source Vcc1 ranges between a minimum value, $Vcc1_{min}$, and maximum value $Vcc1_{max}$. The angle $\Delta\theta$, responsible for the modulation, also ranges between a minimum and maximum value, so that the function $F(\Delta\theta)$ compensates the variation of Vcc1, keeping the rms voltage constant on the primary sides of the transformers. The variation of $F(\Delta\theta)$ as a function of $\Delta\theta$ is presented in Fig. 4.

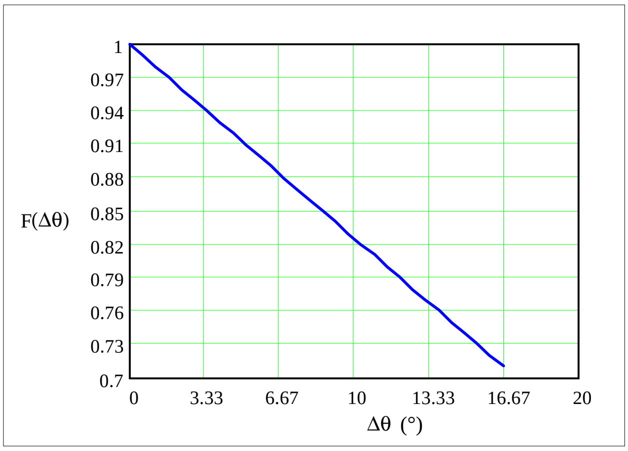


Fig. 4 – Variation of $F(\Delta\theta)$ as a function of $\Delta\theta$.

When voltage Vcc1 is at its minimum value, the modulation angle $\Delta\theta$ also assumes its minimum value, maximizing the function $F(\Delta\theta)$ and maintaining the rms voltage on the primary side at its rated value. On the other hand, when Vcc1 is at its maximum value the angle, $\Delta\theta$, also will be at its maximum, minimizing $F(\Delta\theta)$ and maintaining the rms voltage constant, again.

The minimum angle, $\Delta\theta_{min}$, is zero so that $F(\Delta\theta)_{max}$ is equal to one. The minimum value of function $F(\Delta\theta)$ is given by (11).

$$F(\Delta\theta)_{min} = \frac{Vcc_{1min}}{Vcc_{1max}} \quad (11)$$

The maximum modulation angle, $\Delta\theta_{max}$, is defined by (12).

$$\Delta\theta_{max} = \pi - 2\arccos\left(\frac{1 - F(\Delta\theta)_{min}}{2}\right) \quad (12)$$

B. Determination of the transformers turns ratios.

After obtaining the equation that calculates the rms voltage on the primary side of the transformers, the transformers turns ratios for the Delta-Wye and the Delta-Zig-Zag transformers can be calculated. The Delta-Wye transformer turns ratio is given by (13).

$$n_Y = \frac{V\sec_{rms}}{0.78 \cdot \left[\left(Vcc_{1_{min}} .F(\Delta\theta_{min})\right) + \left(Vcc_{1_{max}} \cdot F(\Delta\theta_{max})\right)\right]} \quad (13)$$

$V\sec_{rms}$ is the rms voltage on the Wye secondary side which is equal to half of the rms output voltage.

The Delta-Zig-Zag transformer turns ratio is related to the Delta-Wye transformer turns ratio, as given by (14).

$$n_{ZZ} = \frac{n_Y}{\sqrt{3}} \quad (14)$$

C. Determination of the output filter parameters.

In order to attenuate the harmonics which were not eliminated by the modulation, an output filter was required. The filter for each phase has the configuration shown in Fig. 5.

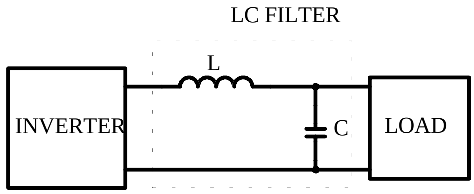


Fig. 5 - Filter model for each phase.

The chosen cut-off frequency, fc, is the filter resonance frequency, therefore the module of the filter inductor, L, will be given, as a function of the filter capacitor, C, by (15).

$$L(C) = \frac{1}{C \cdot (2 \cdot \pi \cdot fc)^2} \quad (15)$$

The current amplitude in C is represented by (16).

$$i_C(C) = 2 \cdot \pi \cdot fs \cdot C \cdot Vo\,, \quad (16)$$

where Vo is the desired output voltage.

The amplitude of the current across inductor L is given by (17).

$$i_L(C) = \sqrt{i_C(C)^2 + io^2}\,, \quad (17)$$

where io is the desired output current.

Equation (18) represents the inductor voltage.

$$v_L(C) = 2 \cdot \pi \cdot fs \cdot L(C) \cdot i_L(C) \quad (18)$$

The voltage's module supplied by the inverter at the filter's input is represented by (19).

$$Vin_f(C) = \sqrt{v_L(C)^2 + Vo^2}\,, \quad (19)$$

The fundamental apparent power component, which is provided by the inverter to the output filter and to the load is given by (20).

$$N(C) = Vin_f(C) \cdot i_L(C) \quad (20)$$

The capacitor's and inductor's reactive powers are given, respectively, by (21) and (22).

$$Q_C(C) = Vo \cdot i_C(C) \quad (21)$$

$$Q_L(C) = v_L(C) \cdot i_L(C) \tag{22}$$

The graphical representations of the apparent power variation provided by the inverter and the reactive powers of the capacitor and the inductor are shown in Fig. 6.

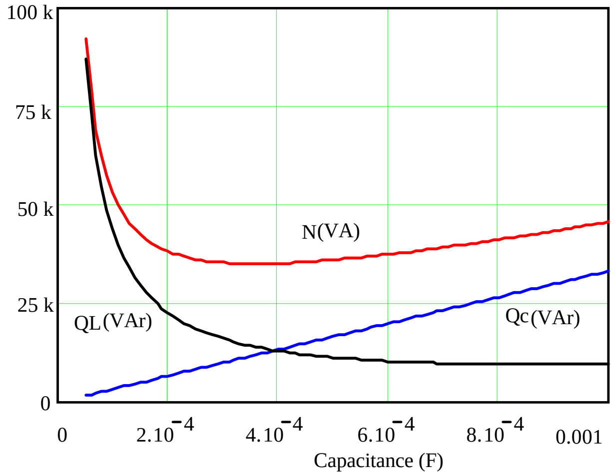


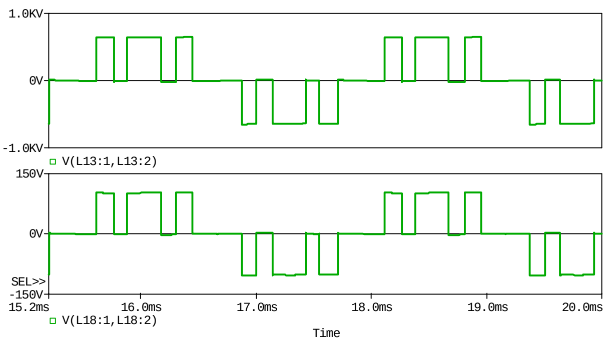
Fig. 6 – Apparent and reactive powers as a function of the filter capacitance.

From the graph of Fig. 6, an appropriate value for C is chosen. This value must be such, that the values of the inductor's and capacitor's reactive powers are similar and that the apparent power supplied by the inverter does not increase rapidly. With this value of C, and using (15), the value of inductance L is calculated.

IV.SIMULATION RESULTS

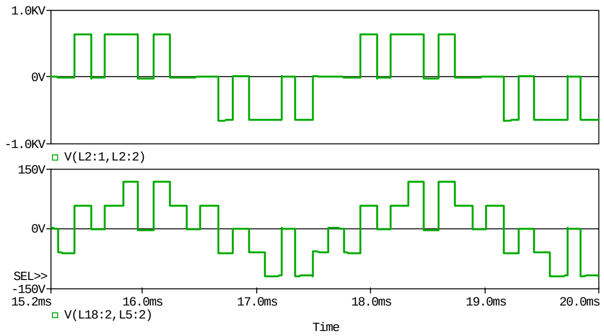
Following the theoretical studies, a 90kW / 400Hz inverter has been designed having a rms output voltage equal to 115V. The simulation was realized for the most critical harmonic distortion situation, which occurs when the modulation angle is maximum.

Fig.7 (a) presents the voltages on the primary and the secondary sides for one phase of the Delta-Wye transformer. The voltages across the primary and secondary sides of the Delta-Zig-Zag transformer are shown in Fig. 7(b).



Primary voltage(upper) and secondary voltage(lower) on Delta-Wye transformer.

(a)

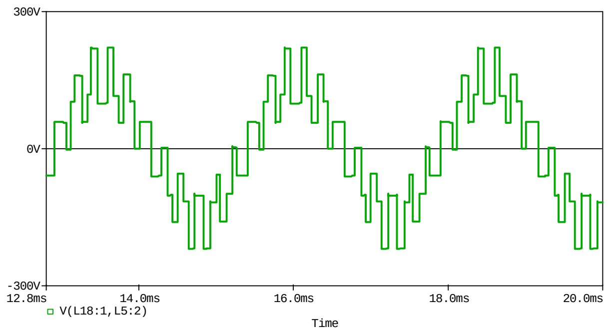


Primary voltage(upper) and secondary voltage(lower) on Delta-Zig-Zag transformer.

(b)

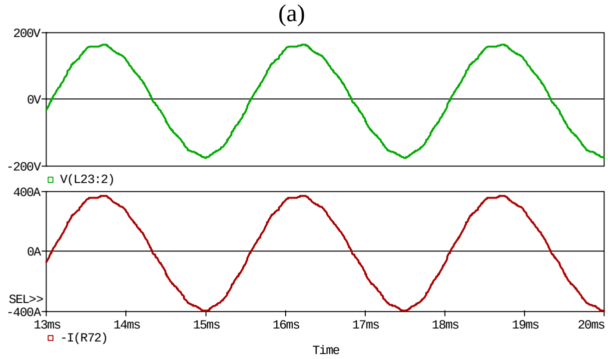
Fig. 7 - Simulated Waveforms.

The total secondary voltage that supplies the output filter of each phase is presented in Fig. 8(a). Fig. 8(b) presents the output voltage and current that will supply the load per phase. It can be observed that the output waveforms have a low harmonic distortion.



Total secondary voltage.

(a)



Output voltage (upper) and output current (lower).

(b)

Fig. 8 - Simulated Waveforms.

V.IMPLEMENTED PROTOTYPE

After the simulation stage, a prototype was implemented with the following main parameters.

Minimum rms input line voltage: 380V-10%
Maximum rms input line voltage: 440V+10%
Three-Phase output power: 90kW
Operation frequency: 400Hz

Rms output phase voltage: 115V
Maximum output voltage THD% : 3%
Delta-Wye transformer turns ratio: 0.16
Delta-Zig-Zag transformer turns ratio: 0.092
Output filter capacitance: 390uF
Output filter inductor: 65uH
Inverter switches: IGBT module SKM300GB124D

The output phase voltage harmonic specter for the rated operation condition is presented in Fig. 9.

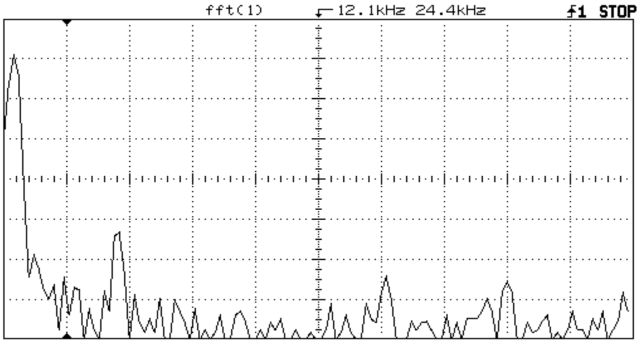


Fig. 9 – Harmonic specter of the output phase voltage.

Two pictures of the external equipment’s appearance are presented in Fig. 10.

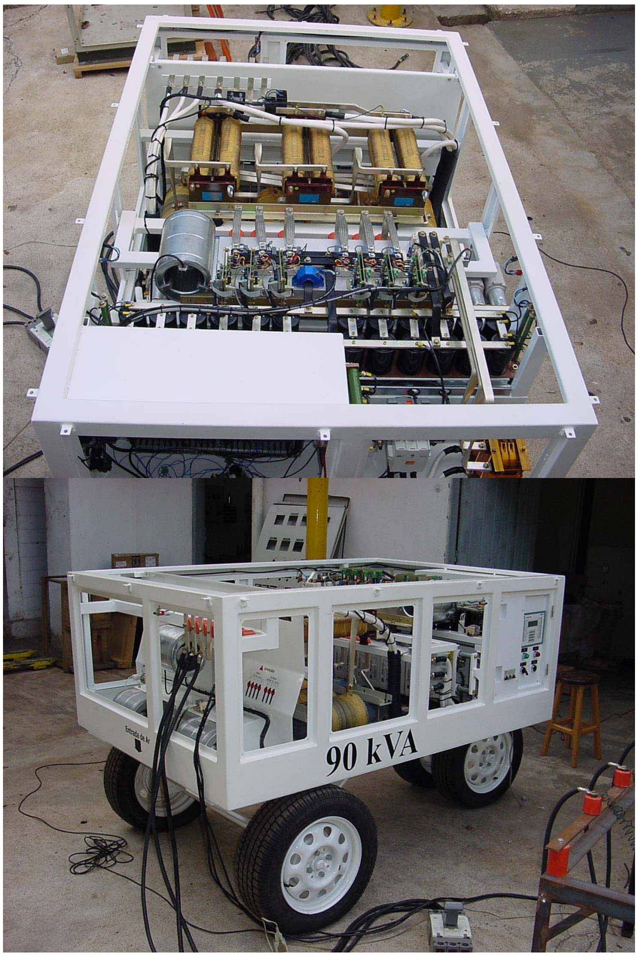


Fig. 10 – Pictures of the implemented prototype.

The main problems in the practical implementation were the overheating of the Delta-Wye and, mainly, the Delta-Zig-Zag transformers and the electromagnetic interference that caused an improper performance of the short circuit protection of the inverter’s switch command drivers. To solve the problem of the transformers’ heating, caused by iron losses, it was necessary to change the positions of the components in order to improve air circulation.

VI. CONCLUSIONS

A 90kVA/ 400Hz inverter for ground support for aircrafts was presented in this paper.

This topology has a low total harmonic distortion in result of a special connection for the transformers that cancels certain harmonic components. The output filter attenuates the remaining harmonic components.

The modulation technique, chosen to control the rms value of the output voltage, was very efficient by maintaining this value constant for high variations of the inverter’s input voltage.

Following the theoretical studies, a prototype has been designed and implemented, rated at 90 kW, 400 Hz, and having a rms output voltage equal to 115 V. The prototype is operating in an airport and its experimental results confirmed the theoretical analysis made for the inverter.

VII. ACKNOWLEDGEMENT

The authors would like to thank the company Grameyer Equipamentos Eletrônicos Ltda for the pictures in Fig. 10.

VIII. REFERENCES

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