NEW 3-PHASE STEP-UP DC-DC CONVERTER WITH 3-PHASE HIGH FREQUENCY TRANSFORMER

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***Abstract* – This paper presents a new 3-phase step-up DC-DC converter with a 3-phase high frequency isolation transformer. Its characteristics are: high frequency isolate transformer, low input ripple current and reduced output voltage ripple. The use of three-phase symmetrical transformer instead of single-phase transformers improve the utilization of the available apparent power of transformer also weight and size reduction are expected. The proposed three-phase inverter circuit presents, a low input ripple current because it acts as non- pulsed source current independently of the converter's operation modes, CCM, DCM or converter's operation regions (table 1). The output voltage ripple is reduced due to the three-pulse output current and consequently, a small capacitance value is required. The three only switches, connected at the same reference, establish a quite simple command and control circuits they do not required any isolation. The main expressions for a design in continuous conduction mode and simulation results for a 6.8 kW simplified design example are presented.**

I. INTRODUCTION

The great necessity in several areas, highlighting the industrial sector, for switch mode power converters with larger power ratings at the end of 80´s were the starter point for the high frequency three phase dc-dc converter emerging.

Since the first three phase dc-dc isolate converter introduced by PRAZAD *et al.* 1988 [1], up until nowadays, the three phase dc-dc development follows two ways, both with the same goal: to increase the electronic power density ratings. The new topologies are one way and have important propositions [1], [4], [5]. The second way is the soft commutation with its main contributions [2], [3], [5].

The typical architecture of a high frequency three phase dc-dc isolate converter is depicted in Fig. 1. In the input stage, the mostly common configuration is the stage operates like a voltage source, while the output stage has current source characteristics, [1], [2], [3], [5], [6].

The advantages of three phase dc-dc isolate solutions are:

- Reduction of input and output filters volume;
- reduction of weight and size of the isolation transformers,
- lower rms current levels through the power components, when compared to single phase solutions for same power ratings.

In the other side, employing three phase solutions increase circuit's complexity, and the number of components. This characteristics can reduces reliability of application.

The three phase step-up dc-dc isolate converter presents in this article, Fig. 2, has all of the main advantages of the three phase solutions presented up until today. Moreover, the reduced number of switches plus the voltage step-up characteristic improve efficiency and reduces, together with high switching frequency, the output filter volume, respectively. In this paper is presented the three phase step-up dc-dc isolate converter, Fig. 2.

This new topology has similar advantages of three phase dc-dc solutions. However, reduced number of switches plus the voltage step-up characteristic together with high switching frequency, 50 kHz, improve the converter's efficiency and reduces the volume of the output filter, respectively. Furthermore, due to input current source and step up voltage characteristics, this topology can be adopted in all types of applications supplied by alternatives energy sources, like battery or photovoltaic arrays an the newer, fuel cell systems. Three converter's operation regions are defined, which, depends of the number of switches that are on overlapping command conditions, Table 1. Simulation results for a 6kW, 48 V at the input and 400 V at the output are presented.

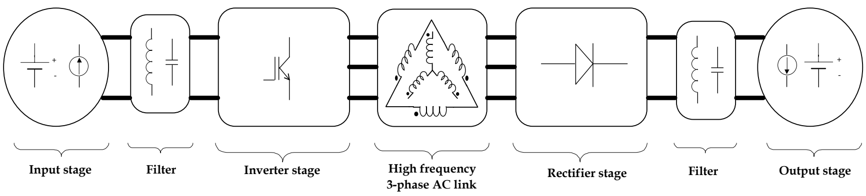

Fig. 1 - Typical 3-phase DC-DC converter architecture.

II. THE PROPOSED CIRCUIT AND PRINCIPLE OF OPERATION

A) Circuit Description

Fig. 2 shows the power-stage of the proposed circuit. The left side circuit (inverter) comprises three inductors and three switches connected in a DC link. The right side circuit is a traditional three branches six diodes rectifier with a capacitive output filter. A high-frequency 3-phase transformer makes the link between two sides. The 3-Phase step-up DC-DC isolate converter characteristics are:

- The use of a three-phase symmetrical transformer instead of a single-phase transformer allows a better utilization of the available apparent power of transformer and also weight and size reduction are expected;
- the proposed three-phase inverter (left-side) circuit presents a low input ripple current because it acts as non-pulsed source current independently of the converter's operation modes or region;
- the output voltage ripple is reduced due the three-pulse output current; consequently a small capacitance value is required;
- the three only switches connected at the same reference, confers a simplicity of command and control circuits,
- the voltage applied across the switches is reduced employing isolation transformer.

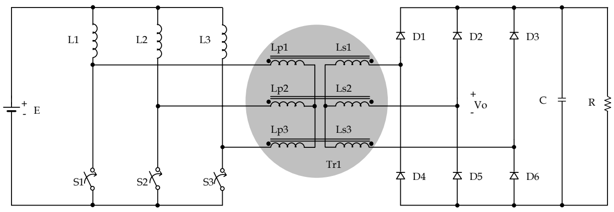

Fig. 2 – The new 3-phase step-up DC-DC isolate converter diagram.

B) Analysis of operation

To facilitate the analysis of the circuit operation, Fig. 3 shows a simplified circuit diagram. In the simplified circuit, Tr1 is modeled as an ideal transformer with turns ratio n=1. Assuming that its magnetizing inductance is high enough so it can be neglected. Besides, it is assumed that the filter capacitor C is large enough and thus its output voltage ripple is small compared to its DC voltage.

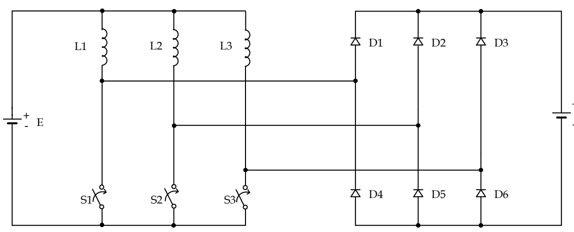

Fig. 3 – Simplified power-stage circuit diagram.

Finally, it is assumed that all semiconductor components are ideal, i.e., they present zero impedance in the on state and infinite impedance in the off state. The power flux transfer and the output/input voltage ratio are controlled by the duty ratio D of the switches. A PWM technique is adopted to the switches S_1, S_2 e S_3. The duty ratio D is defined as:

$$D = \frac{T_{on}}{T_s} \tag{1}$$

Where:

- t_{on}= the time interval that the switch is kept on and
- T_s= switching time.

C) Operation regions

The circuit proposed has three different operation regions according to the Table 1. Each region differs from each other by the number of the on state switches at the same time (overlapping). For each region the duty cycle ratio can assume different values.

TABLE 1- OPERATIONS REGIONS FOR THE CONVERTER.

Regions	Duty ratio	Switches Status
1	D ≤ 1/3	Prohibited
2	1/3 ≤ D ≤ 2/3	2-switches on
3	D ≥ 2/3	3-switches on

Due to the converter's input current source characteristic, at least one switch must be always in turned on. Hence, the first region, R_1, is prohibited for converter's operation.

III. THEORETICAL ANALYSIS

A) Steady state stage operations

Fig. 4 shows four of six topological stages of the converter's operation during a period of the switching cycle.

1st stage (t_0, t_1) – Fig. 4(a)

At the instant t_0 switch S_1 is turned on joining switches and S_3. They are kept turned on during this stage. The inductances L_1 and L_3 storage energy from E source. The L_2 storage energy is transferred to the load through D_2, D_4 and D_6. The $iD_4(t)$ and $iD_6(t)$ currents are respectively added to $iS_1(t)$ and $iS_3(t)$. This stage finishes at instant t_1 when S_3 is turned off.

2nd stage (t_1, t_2) Fig. 4(b)

At instant t_1 S_3 is turned off and the L_3 and L_2 storage energy is transferred to the load through D_3, D_2 and D_4. The $iD_4(t)$ current is added to $iS_1(t)$. This stage finishes at instant t_2 when S_2 is turned on.

3rd stage (t_2, t_3)) Fig. 4(c)

At instant t_2, S_2 is turned on. The E source energy is storage in the L_1 and L_2 inductances. The L_3 storage energy continues being transferred to the load through D_3, D_4 and D_5. This stage finishes at instant t_3 when S_1 is turned off.

4th stage (t_3, t_4)) Fig. 4(d)

When S_1 is turned off, the L_1 and L_3 storage energy is transferred to the load through D_1, D_3 and D_5. The $iD_5(t)$ current is added to $iS_2(t)$. This stage finishes at instant t_4 when S_3 is turned on again.

5th stage (t_4, t_5) Fig. 4(e)

At instant t_4 S_3 the energy from the E source is storage in the L_2 and L_3 inductances. The L_1 storage energy continues being transferred to the load through D_1, D_5 and D_6. This stage finishes at instant t_5 when S_2 is turned off.

6th stage (t_5, t_6) – Fig. 4(f)

The converter's last stage operation, for a switching period T_s started at the instant t_5 when S_2 is turned off. The energy from the E source storage in the L_2 and L_1 inductances is then transferred to the load through D_1, D_2 and D_6 diodes. The $iD_6(t)$ diode current is respectively added to $iS_3(t)$ switch current. At the end of this stage a converter's operation switching period is finished.

B) Key waveforms

Fig. 5 presents the theoretical key waveforms to the R_3 operating region.

C) Output Characteristic

Fig. 6 shows the three operation regions related to the output characteristic of proposed converter. There it is observed the two modes of conduction of the converter. The output/input gain, q, for each region on the CCM mode is limited in maximum of 3 for R_2 operation area (vertical lines pattern). Otherwise, on R_3 region, horizontal lines pattern, the minimum value of the output voltage in the CCM operation mode is 3.

The q gain, in the DCM operation mode, changes in according to the parametric load expression, given by (2).

$$\overline{I_o} = \frac{I_o f_s L}{E} = \frac{3}{2}\left(\frac{q-1}{q^2}\right) \qquad (2)$$

Where:

- I_o= the load current;
- f_s= the switching frequency;
- E = input voltage,
- L = the input inductance values.

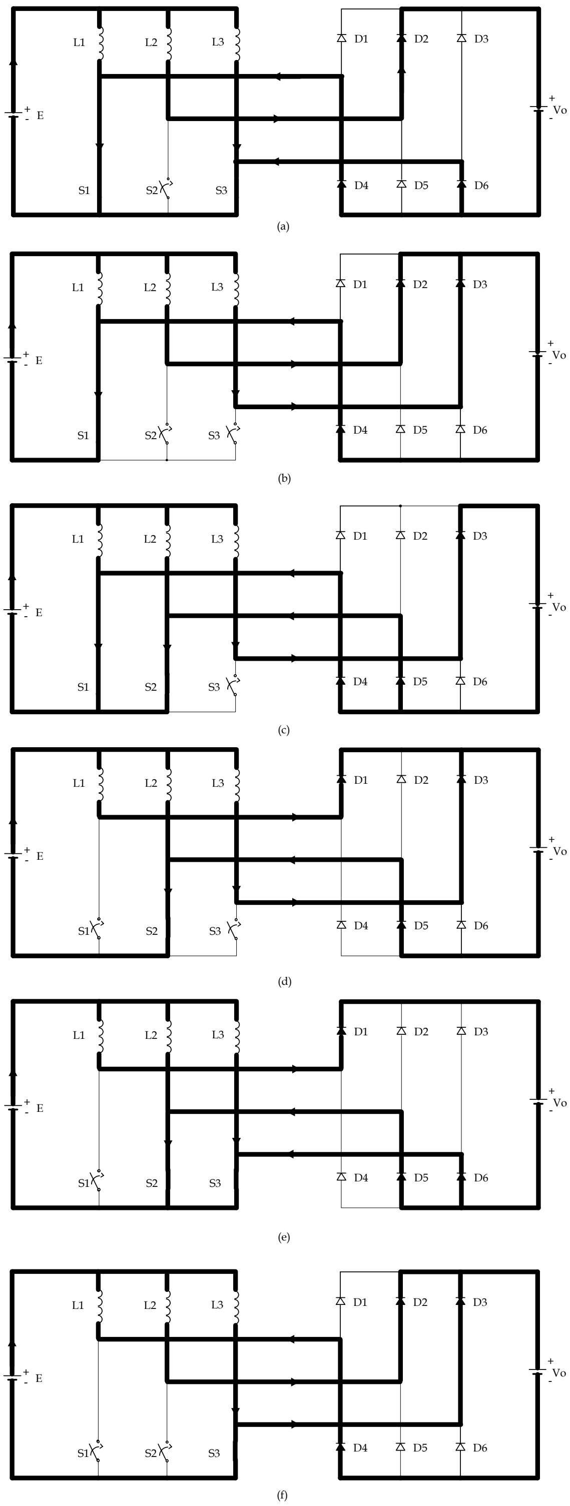

Fig. 4 – Topological stages of proposed converter.

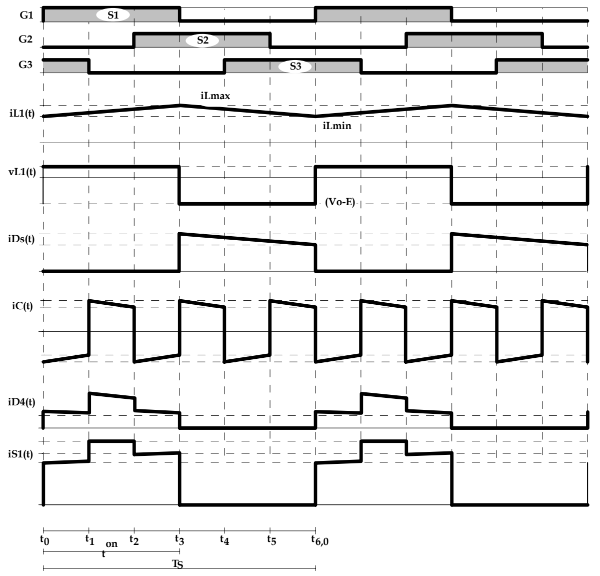

Fig. 5 – Theoretical key waveforms of proposed converter.

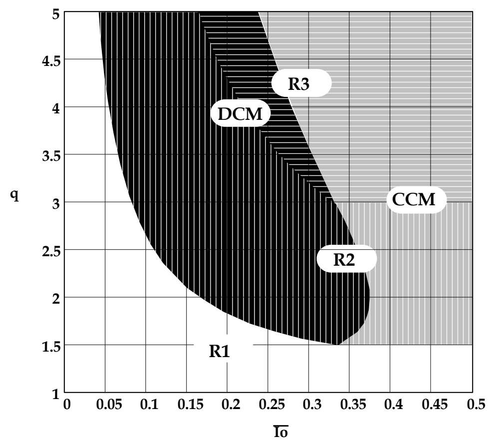

Fig. 6 – Output characteristic of the proposed converter.

IV. Simplified Design Example

The goal of this analysis is to show the utilization advantages of three phase isolation transformer in a three phase step-up dc-dc converter. The simulation results are obtained for a system supplied from a battery array. Similar characteristics can be found in both fuel cell and or photovoltaic array systems. The system specifications are shown bellow.

- Po = 6.8 kW, output power;
- Vo = 450 V, rated output voltage;
- E = 47 V, rated input voltage;
- fs = 50 kHz, switching frequency;
- n=5, transformer's turns-ratio,
- ΔVo = 9 V, output ripple voltage.

A) Determination of voltage gain

From the output and input voltages values, one can obtain (3).

$$q = \frac{V_o}{nE} \tag{3}$$

B) Duty ratio

The duty cycle ratio is given by (4).

$$D = \frac{q-1}{q} = 0.478 \tag{4}$$

C) Determination of the input inductances

The value of the input inductances of each arm of the inverter will be defined taking into account the output characteristic of the converter. As it is interesting operating in the continuous conduction mode, the inductances value will be obtained in such a way that, even with 20% of the converter load stays in the continuous conduction mode. Therefore, the value of the parametric output current is defined for (5).

$$\overline{I_o} = \frac{3}{2}\frac{D^2}{q-1} = \frac{3}{2}\frac{(0.478)^2}{(1.915-1)} = 0.374 \tag{5}$$

The critical input inductances value for 20% of the load current is defined through the equation (6).

$$L_C = \frac{5 \cdot E\overline{I_o}}{f_s I_o} = \frac{5 \cdot 47 \cdot 0.374}{50000 \cdot 15.11} \cong 116\mu H \tag{6}$$

D) Determination of the output capacitance

$$C = \frac{2f_s L I_o q^2(3-q) + V_o q(2q-5) + 3V_o}{18q^3 f_s^2 L \Delta V_o} \cong 3.15\mu F \tag{7}$$

V. Simulations Results

A) Transformer waveforms

Fig. 7 depicts the switch command signals and current and voltage at high frequency transformer windings. Through it, the CCM mode and R2 region of converter operation are confirmed. Although, the asymmetry of the windings currents it doesn't present have DC component, avoiding core saturation. These waveforms can be used to calculate de power processed by the converter. The simulation presents a 1.02 p.u. apparent power, what means a good usage of the high frequency transformer, with small losses during the energy transference.

B) Semiconductors waveforms

Fig. 8 shows the main semiconductor currents for the converter operation region R2. The use of the three phase transformer allows isolation and establishes that the voltage across converter's switches is given by the output voltage referred to the primary side. Then this converter presents characteristics suitable for output voltages higher than the non isolate version or the conventional single phase topologies.

C) Passive elements waveforms

The current and voltage stress are presented at Fig. 9. The curves (b) and (c) shows that the frequency of the output current and voltage on the output filter capacitor is three times the frequency on the switches.

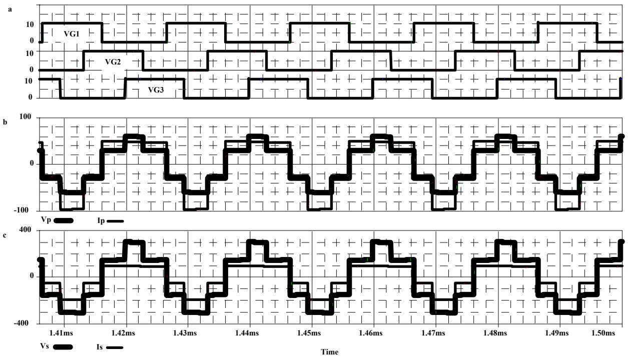

Fig. 7 – Switch's command plus voltage and current through secondary windings waveforms.

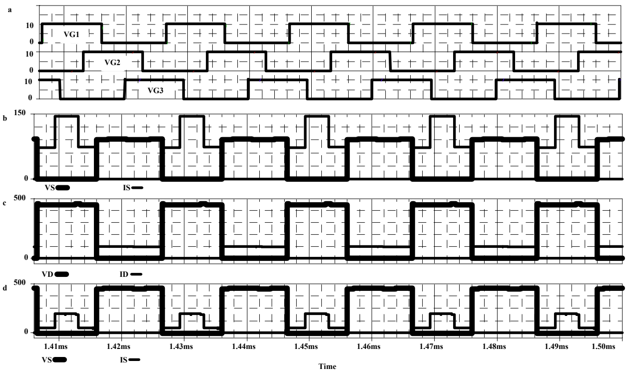

Fig. 8 – Waveforms through semiconductor's elements: (a) switch's commands, (b) current plus voltage waveforms at S1 switch, (c) reverse voltage across diode D1 and (d)voltage and current through diode D4.

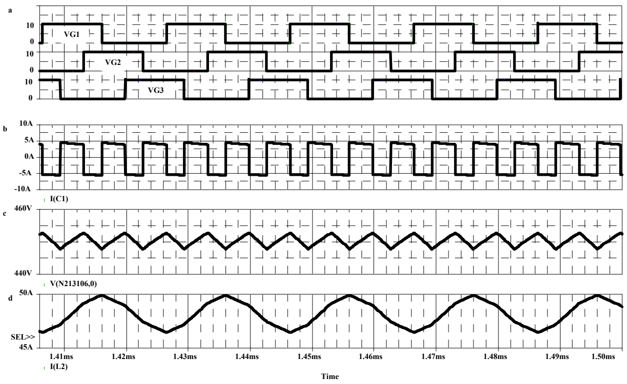

Fig. 9 – Waveforms at passives elements: (a) switch's commands, (b) output capacitor current iC1(t), (c) voltage across the output capacitor (d) input inductor's ripple currents.

VI. CONCLUSIONS

This paper has presented an analysis for a new three-phase step-up DC-DC converter with three-phase high frequency transformer. The proposed converter keeps all advantages of the traditional three-phase dc-dc converters using a reduced number of switches. In addition, the use of the high frequency isolation transformer reduces weight and size of the converter.

The step up voltage characteristic and the isolation high frequency transformer utilization allow large range gain between output and input voltage.

The characteristics of this converter show that the new proposition achieves high power density. This improves its performance at high power levels as can be observed through a simplified design example and its simulations results.

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