ELEMENTARY AND SELF-LIFT NEGATIVE OUTPUT LUO DC-DC CONVERTERS USED IN HYBRID CARS

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In this paper a new design concept of the electrical propulsion system for a hybrid car is introduced. A scheme containing two converters is proposed for the two basic functions of a car (going forward or in reverse). The paper will focus mainly on the reverse function, for which a negative output converter is needed. For this, the elementary negative output Luo converter and self-lift Luo converter are introduced and analyzed. The mathematical equations are deducted step-by-step and the circuit is simulated in PSspice. A comparison between these two converters is done, enhancing the improvements brought by the second one.

Keywords: Hybrid Car, Luo converter, Negative Output, Self-Lift Luo Converter, Power Electronics.

1. Introduction

Power electronics started in the early 60s with the invention of the first power thyristor. Since then, new electromechanical devices that have been developed to convert electric energy have been replaced by static frequency converters and many other new applications have been developed. Power electronics mainly deals with the control and conversion of electric power used for specific applications that have different requirements.

Electric cars rely only on electric motors for propulsion, as hybrid ones use electric motors to assist their internal combustion engines for locomotion. Practically, the hybrid car use both the electrical power supplied from batteries on board of the car or from a fuel-based motor on board. The other big advantage of a hybrid car is that it has the ability to reuse the dissipated energy when braking and use it to further load the batteries, this technology being called regenerative braking.

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Motors used in this kind of machinery are devices that can run in two opposite modes. This does not mean that the two modes of the motor run backwards from each other but that the shaft spins in the same way. The change of direction will be the flow of electricity. This paper approaches the electric feature of the hybrid car with its subsystems. Currently the most approached method is transforming the direct current (DC) into alternative current which can alternate to both polarizations as it flows in the circuit, thus ensuring both possible directions (fig.1). The problem is that the DC current flows unidirectional into the circuit. This will be the starting point for this paper as a new configuration will be put to analysis as one that will use two converters used to provide voltages of different polarity in order to assure both the reverse and forward function of the car.

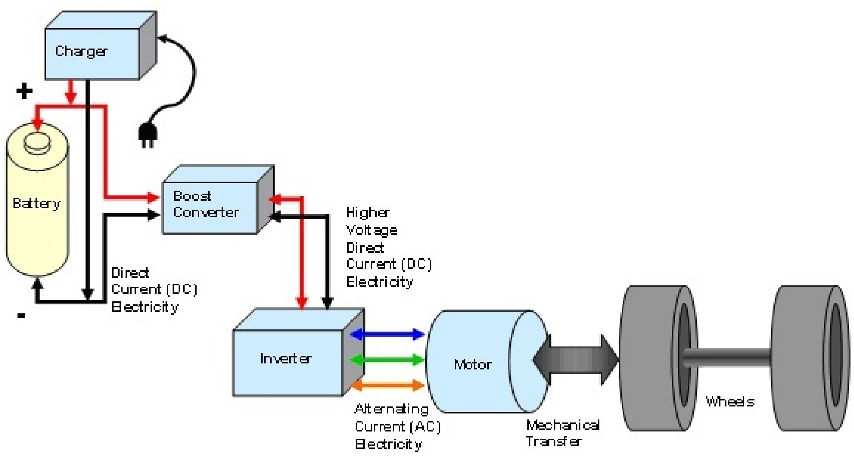

Fig. 1. General Diagram of classical hybrid car

DC to DC converters are important components used in systems that need to be supplied with electrical power especially in mobility solutions that require a battery power source. They will act as an interface between the battery and the load, offering the required voltage levels needed for the consumer. Taking into consideration present data regarding the DC-DC converters, they were split in six generations of converters, with regards to their effects, shape, polarity of the circuit output voltage [3]. The first generation contains the classical ones, as the second generation has the multi-quadrant converters. The third one consists in the switched component converters and the fourth one has the soft-switching ones. The fifth generation contains the synchronous rectifier converters as for the last one it contains the multi-element resonant power ones.

Currently, two important characteristics are needed to be considered in designing a dc converter of high performances. One of them would be to obtain high-voltage conversion ratios and the second one would be to obtain a negative to positive path for the voltage conversion without isolation.

Luo converters are recently developed dc-dc converters. The negative output Luo circuit provides the transformation of positive input voltage to negative output one. The classical negative output Luo converter with its two possible switch states of the is shown in fig 3. The circuit contains an electronic pump composed by S, L, D, C components and a low pass filter with C, L_0, C_0.The capacitor C is necessary to store and transfer the energy from the source to the load. The function of the low pass filter will be also to reduce the output voltage and the currents ripple.

2. Topology of the new system

As an interface between the battery and motor, the converters role is also to perform a step up of the voltage supplied from the battery cells. This paper intends to introduce a new possible concept for designing the electrical propulsion system of a hybrid vehicle as in fig. 2.

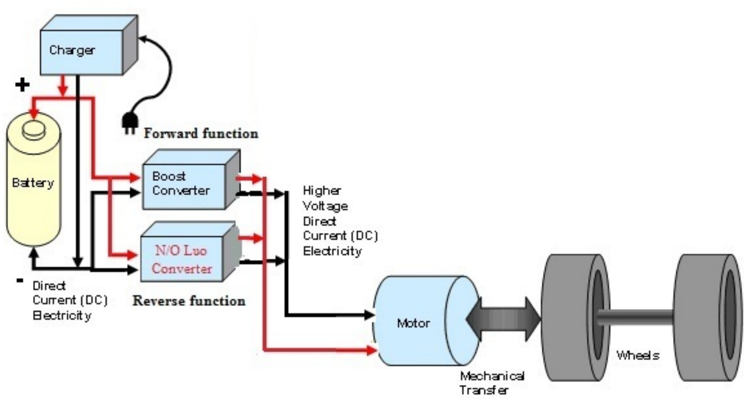

Fig. 2. General Diagram of the new concept of hybrid car

As mentioned before, the new concept involves the use of DC current through all the electrical circuit BUS. Being able to do this means that the circuit would need to have two converters at the interface of the battery and the motor, to perform both functions of forward and backwards spinning. This paper will deal with the reverse gear function of the car, by using a negative output voltage converter in order to obtain a negative current at the output that will offer this required function. In order to perform the step-up function of the voltage supplied by the battery and, at the same time, to obtain a negative voltage, a negative output Luo converter has been tested for this function first using the classical scheme of the converter and then its improved self-lift version. The battery pack considered in this simulation contains a *"n cells"* series system containing 168 serried 1.2V cells grouped in 28 modules, which will offer around 200V output voltage to the converter.

3. Analysis and Simulation of elementary negative output Luo converter

During the period when the switch is on, the inductor absorbs energy from the source and the current I_L is increasing. In this time, the inductor L_0 will deal with transferring the energy from the capacitor C to the load R, also keeping the output current continuous. When the switch is off, the current crossing the source will be zero.

The current I_L flows through diode D to charge capacitor C. Inductor L transfers the stored energy to the capacitor and to the load R.

The voltage transfer gain of this converter in continuous conduction mode is:

$$N = \frac{V_O}{V_I} = \frac{I_I}{I_O} = -\frac{D}{1-D} \quad (1)$$

The current through *L* inductor increases and is supplied by V_i during the conduction period of the static switch. Because of this, the ripple of current i_L is:

$$\Delta i_L = \frac{DTV_I}{L} \quad (2)$$

$$I_L = I_{C-off} + I_O = \frac{I_O}{1-D} \quad (3)$$

The variation ratio of current i_L is then:

$$\xi = \frac{\Delta i_L}{I_L} = \frac{V_I}{I_O L} D(1-D)T = \frac{D(1-D)R}{NfL} = \frac{D^2}{N^2}\frac{R}{fL} \quad (4)$$

The variation of the capacitor C voltage is:

$$\Delta v_C = \frac{D}{C} T I_O$$

so its variation ratio will be:

$$\rho = \frac{\Delta v_C}{V_C} = \frac{I_O}{CV_O} DT = \frac{D}{fRC} \quad (5)$$

The ripple of the current i_{LO} is:

$$\Delta i_{LO} = \frac{D}{8f^2 L_O C} I_O \tag{6}$$

If I_{LO} is considered to have the same value as I_O, the variation ratio of the current i_{LO} is:

$$\xi = \frac{\Delta i_{LO}}{I_{LO}} = \frac{D}{8f^2 L_O C} \tag{7}$$

The ripple and the variation ratio of the voltage on capacitor C_O at the output are:

$$\Delta v_{CO} = \frac{A}{C_O} = \frac{DT}{64f^2 C C_O L_O} I_O = \frac{D}{64f^3 L_O C C_O} I_O \tag{8}$$

$$\varepsilon = \frac{\Delta v_{CO}}{V_{CO}} = \frac{D}{64f^3 L_O C C_O V_O} I_O = \frac{D}{64f^3 L_O C C_O R} \tag{9}$$

In discontinuous conduction mode, the current through diode D will be zero during off state of the switch. The constraint for which the circuits works in discontinuous conduction mode is:

$$\frac{D^2}{N^2}\frac{R}{fL} \geq 1$$

In discontinuous conduction mode the current through diode D is not zero during the period between DT and

$$t_1 = [D + (1-D)m_E]T$$

where m_E is the filling efficiency and is defined as:

$$m_E = \frac{N^2}{D^2}\frac{fL}{R}$$

Because current i_D becomes zero at:

$$t = t_1 = [D + (1-D)m_E]T\ ,$$

the voltage on the capacitor C could be calculated as:

$$V_C = \frac{D}{(1-D)m_E} V_I = D(1-D)\frac{R}{fL} V_I \tag{10}$$

The output voltage in discontinuous conduction mode is:

$$V_O = -\frac{D}{(1-D)m_E} V_I = -D(1-D)\frac{R}{fL} V_I \tag{11}$$

In order to simulate the converter working mode. the following values were used after running multiple simulations:

- Input Voltage V_I =200V
- The static switch period T=20us, with f=50 kHz
- The conductivity ratio of the switch is D=0.6
- L=10mH C=20uF L_0=10mH
- C_0=20uF R=20 Ω
- D is an ideal diode with snubber [5]

For the above exposed values, following the mathematical models exposed before, we obtained after calculus:

$V_O = -300V$ $N = 1,5$

$\Delta i_{L1} = 240mA$ $\xi_1 = 6.4\times10^{-3}$

$\Delta v_C = 0,9V$ $\rho = 0.03$

$\Delta i_{Lo} = 2,25mA$ $\xi = 15\times10^{-5}$

$\Delta v_{CO} = 0.28125mV$ $\varepsilon = 0.93\times10^{-6}$

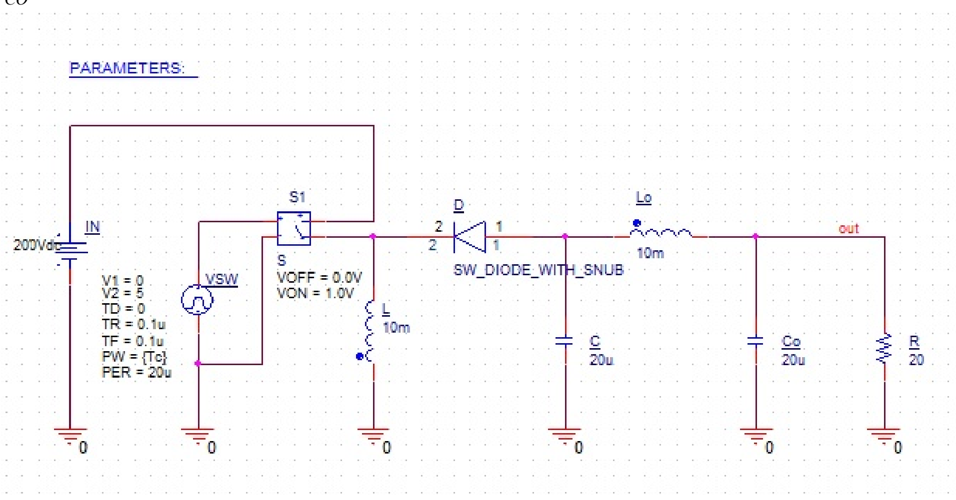

Fig. 3. Orcad scheme of elementary N/O Luo converter

After simulating the circuit in fig.3 the waveforms in fig.4 are obtained and they confirm the mathematical analysis done before.

However, the results that are obtained are not so good considering that the hybrid car needs a real step-up converter in order to obtain a higher voltage level on the bus supplying the electrical motor. As the equation and the graphic shows, if we obtain a small ripple for both the output voltage and the current the boost of the voltage is not significant. In order to enhance these performances the self-lift converter is further analyzed.

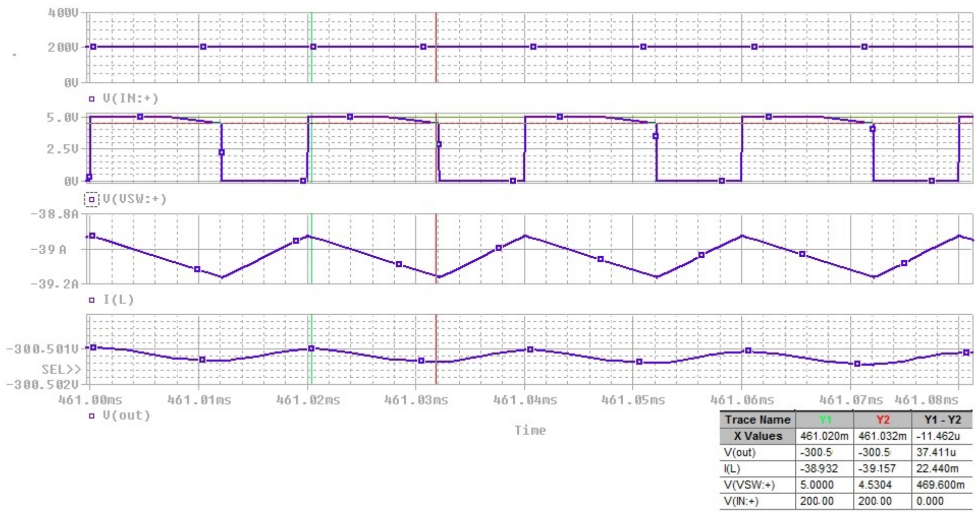

Fig. 4. N/O Luo converter simulated in PSpice

4. Self-Lift N/O Luo converter analysis and simulation

The Self-Lift N/O Luo derives from elementary N/O Luo. The difference from the elementary one is that a capacitor and a diode where added to the circuit.

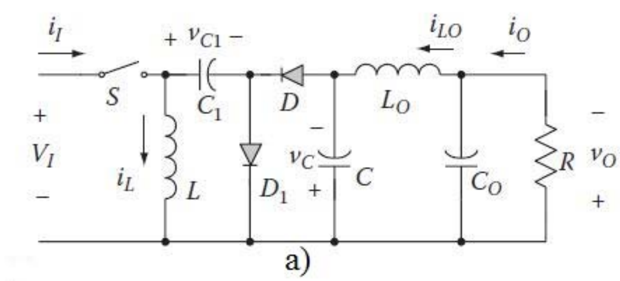

Fig.5. Self- Lift N/O Luo converter

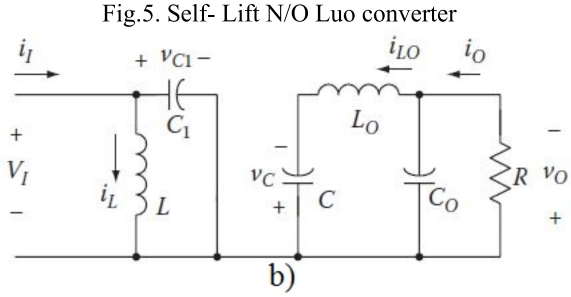

Fig.6. Equivalent circuit for Self-Lift N/O Luo converter when switch S is ON

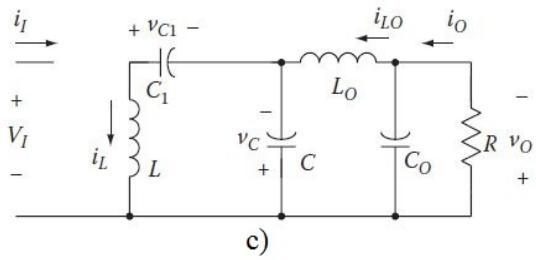

Fig.7. Equivalent circuit for self-Lift N/O Luo converter when switch is OFF

The capacitor has the responsibility to lift the voltage V_c with the input V_I voltage. During conduction of the static switch, D1 conducts and D is blocked. During OFF , diode D conducts and D1 is blocked, as it can be seen from group figures 5 6 and 7.

During balanced working mode of the converter, the average voltage on the inductor is zero, so $V_c = V_{co} = V_o$.

During ON state of the switch, the voltage on the capacitor C1 is equal to the input voltage. Because it is supposed that C=C1 and they have sufficient values, it can be said that $V_{C1} = V_I$.

The current through L inductor, i_L increases during ON state until it reaches the value of the input voltage and decreases during OFF until $-(V_C - V_{C1})$. The output voltage will be:

$$V_O = V_C = V_{CO} = -\frac{1}{1-D}V_I \tag{12}$$

The transfer gain of the converter is:

$$N = \frac{V_O}{V_I} = \frac{I_I}{I_O} = -\frac{1}{1-D} \tag{13}$$

As all the elements of the circuit are considered ideal, the power loses associated to them are negligible. Than the output power of the circuit is the same as the input power [7]. Starting from this input and using (13), the dependency between the input and the output current is given by:

$$I_I = -\frac{1}{1-D}I_O \tag{14}$$

The capacitor C acts as a low pass filter, so $I_{L0} = I_o$.

Using the same analogy as in the previous chapter, the variation ratios of the currents are given by the equations below:

$$\xi_1 = \frac{\Delta i_L}{I_L} = \frac{V_I}{I_I L} DT = \frac{D(1-D)^2 R}{fL} = \frac{D}{2N^2}\frac{R}{fL} \tag{15}$$

$$\xi_2 = \frac{\Delta i_{LO}}{I_{LO}} = \frac{D}{16 f^2 L_O C} \tag{16}$$

$$\varepsilon = \xi_1 = \frac{D}{2N^2}\frac{R}{fL} \tag{17}$$

The variation ratios of the voltages are described by the following equations:

$$\rho = \frac{\Delta v_C}{V_C} = \frac{D}{2fCR} \tag{18}$$

$$\sigma_1 = \frac{\Delta v_{C1}}{V_{C1}} = \frac{N}{2fC_1 R} \tag{19}$$

$$\varepsilon = \frac{\Delta v_O}{V_O} = \frac{D}{128 f^3 L_O C C_O R} \tag{20}$$

The self-lift negative output Luo converter is working in discontinuous conduction mode if the current i_D is zero at moment t=T, otherwise the circuit is working at the limit between the two conduction modes. The variation ratio of the current i_D is 1 when the circuit is at the limit between the working modes.

Using (15) and the convention $L_{ech} = L$ and $z_N = R/fL$, the border between continuous conduction mode and discontinuous conduction mode can be defined as:

$$M_B = \sqrt{D}\sqrt{\frac{R}{2fL_{eq}}} = \sqrt{\frac{Dz_N}{2}} \tag{21}$$

When $N > M_B$, the circuit is working in discontinuous conduction mode. In this case, the current through diode D, i_D is decreasing to 0, at:

$$t = t_1 = [D + (1-D)m]T\ ,$$

where DT< t_1 <T and 0<m<1 and m is the current efficiency filling factor, that can be defined as:

$$m = \frac{1}{\xi} = \frac{N^2}{D}\frac{fL}{R} \tag{22}$$

In discontinuous conduction mode, the current through inductor L is increasing during the ON state of the switch and it is decreasing during DT and (1-D)mT . In the same time, the voltage increases until V_I and then decreases until

$-(V_C - V_I)$. Therefore:

$$V_I DT = -(V_C - V_I)(1-D)mT$$

Using (12) and the fact that $V_{C1} = V_I$, the output voltage is:

$$V_O = -\left[1 + \frac{D}{(1-D)m}\right]V_I = -\left[1 + D^2(1-D)\frac{R}{fL}\right]V_I \tag{23}$$

The gain ratio in discontinuous conduction mode is then:

$$-M_{DCM} = 1 + D^2(1-D)\frac{R}{2fL} \tag{24}$$

In order to simulate the circuit the following values have been used:

- Input Voltage $V_I = 200$V
- The static switch period T=20u, with f=50 kHz
- The conductivity ratio of the switch is D=0.6
- L=10mH C=20uF L_0=10mH C_0=20uF R=50 Ω
- D is an ideal diode with snubber [5]

With the chosen values above the following mathematical calculus is done using the equations deduced before:

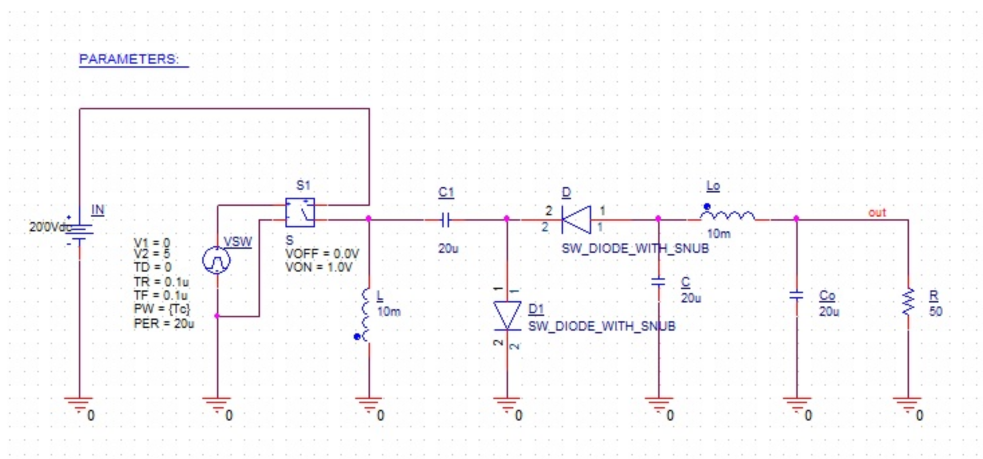

Fig. 8. Orcad scheme of self-lift N/O Luo converter

$V_O = -500V$ $N = -2{,}5$

$\xi_1 = 9.6\times10^{-3}$ $\xi_2 = 0.075\times10^{-3}$ $\xi = 9.6\times10^{-3}$

$\rho = 0.006$ $\sigma_1 = 0.025$ $\varepsilon = 0.18\times10^{-6}$

As it can be seen for the obtained values, the self-lift version of the N/O

Luo converter offers better performances from voltage level point of view. This offers a stepped up voltage at the output of the battery. Also the variations calculated are very small, which means lower ripples of the current and voltage.

The waveforms obtained in fig. 9 confirm the mathematical results obtained in the previous equations.

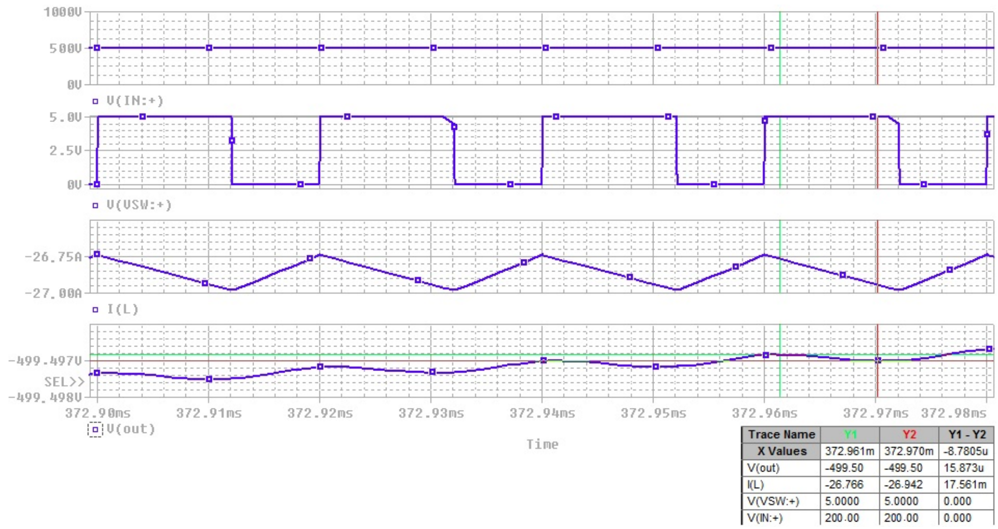

Fig. 9. Self-Lift N/O Luo converter simulated in PSpice

5. Conclusions

The negative output elementary and the self-lift Luo converters are recently developed DC-DC converters. They both can perform a step-up conversion from positive input DC voltage to a negative DC voltage. The voltage lift technique has been introduced to enhance the performances of the elementary converter. It has been used due to its simplicity and relatively ease of use [8].

Because of this new technique, higher voltage gains have been made possible to obtain than in the elementary converter's case. As we can conclude from (20), in discontinuous conduction mode, by increasing the load resistance R, a higher output voltage can be obtained. It also allows voltage to increase on a step by step arithmetic progression. In order to limit the effect of the parasitic elements onto the output voltage and power transfer, the conductivity ratio D should not be higher than 0.9. In this paper a value of 0.6 was chosen for this type of converter.

The results obtained from the simulation of the circuits are quite good and prove that the N/O Luo converter, especially the self-lift version of it, is a good candidate to be used in the this newly proposed topology of the hybrid car. The main improvements brought by this new topology are that the costs of the electrical system of the car will decrease, as the inverters won't be needed anymore.

Another advantage will be that the components of the converter will have better protection, as the second converter will drive to off periods for the first one, thus offering the premises for extending the components life.

These types of converters could be also used in other industrial applications, as in cement manufacturing industry, TGV trains, where high output voltage easily obtained especially with the self-lift Luo converter are needed [9].

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