

Combined Circuit Model for a Four Quadrant Operating Luo-Converter

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Abstract: This work presents a combined circuit, as a new methodology, for a four-quadrant operation converter using LUO's configuration based on the model proposed by Luo and Hong Ye. The combination conjugates two different circuits, each one works for controlling two of the four quadrants or modes respectively. Additionally, this paper presents simulation results for the proposed system in order to verify its characteristics and functionality.

Keywords: Luo DC/DC converter, four quadrant operation, open loop speed control for a DC motor.

Modelo de Circuito Combinado Para Operación en Cuatro Cuadrantes, Convertidor de Luo

Resumen: Este trabajo presenta un circuito combinado, como una nueva metodología para uso de convertidores para operación en cuatro cuadrantes que utilizan la configuración de LUO, basado en el modelo propuesto por Luo y Hong Ye. La combinación combina dos circuitos diferentes, cada uno funciona para controlar dos de los cuatro cuadrantes o modos, respectivamente. Además, este documento presenta resultados de simulación para el sistema propuesto con el fin de verificar sus características y funcionalidad.

Palabras clave: Convertidor DC / DC de Luo, operación en cuatro cuadrantes, control de velocidad en circuito abierto para un motor DC.

1. INTRODUCTION

DC/DC converters have been used in many industrial applications which in general perform single quadrant operation. Traditional models like buck, boost and buck-boost converters (Pasha, Jayakumar, & Thiruvonasundari, 2017) have some applications oriented, mostly, to *electrical power generations, photovoltaic and renewable energy sources* (Chilambarasan, Ramesh, & Sujatha, 2014) (Saradha, Mrudhulaa, Priyadharshini, Seyezhai, & Mrdula, 2018) (Prasanna, Kirubakaran, Rahul Kumar, & Rudhran, 2015) (Elavarasu & Christofer, 2018), *power regulation* (Jayachandran, Krishnaxwamy, Anbazhagan, & Dhandapani, 2015) and *energy storage systems* (Manikandan & Vadivel, 2013) (Sanjeevikumar & Rajambal, 2008).

However, the development of circuits capable of operating in four quadrants has become a necessity, especially in applications with smart grids, where it is necessary to control the charge and discharge of batteries or in the case of electric vehicles, where it is necessary to control the direction of the rotor axis in acceleration or braking state of a DC motor. Luo-converters are an example of DC-DC power conversion circuits developed to perform positive to positive DC-DC voltage increasing conversion with high efficiency and near-zero output voltage and current ripples (Luo F. L., 1997).

The proposed LUO circuit depends on two semiconductors used as switches which are driven by a type of PWM signals with constant switching frequency controlled independently. A 4-pole double state switch (4PDS) is used for changing from forward and reverse states.

Each mode is controlled by one switch. Each state determines the output current path (Sujatha, Chilambarasan, & Ramesh, 2015), and to determine the direction of the rotor axis in acceleration or braking state. Multiple motor characteristics have been considered in the simulation tests, in order that the future implementation will be more reliable.

Free quadrant change is available, but it is necessary to consider events like overcurrent in the entrance circuit loop and polarity change in the capacitor. Thus, it is important to determine safe conduction duty ranges to ensure system stability and integrity of the circuit elements, all depends on the characteristics of the loads. In this project, test results are presented for a DC motor load.

The difference between this work and the original proposed by Luo and Hong Ye in (Luo & Ye, Chapter 7 - Multiple quadrant operating Luo-Converters, 2003) is that it presents simulation results for the combined theoretical circuit named by them as

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“Circuit 3” with a little correction discussed in the next section.

2. COMBINED LUO-CONVERTER MODEL

This section describes the combined circuit proposed by Luo and Hong Ye in (Luo & Ye, Chapter 7 - Multiple quadrant operating Luo-Converters, 2003) for four quadrant operation with a small variation, instead from using a three-pole double state switch (3PDS) for the commutation, as proposed in (Luo & Ye, Chapter 7 - Multiple quadrant operating Luo-Converters, 2003) (Luo, Ye, & Rashid, Four quadrant operating Luo-Converters, 2000), to a four-pole double state switch (4PDS) will be used as shown in Figure 1 otherwise, the proper circuit configurations will not be achieved.

The 4PDS switch defines 4 poles (A, B, C & D) and two states for each pole, it means that each pole has a common pin named A, B, C or D and each one of them has two pins, one for a first state (A1, B1, C1 or D1) and another one for a second state (A2, B2, C2 or D2).

V1 is the input voltage source, S1 and S2 are switches that control acceleration and braking modes, D1 and D2 are diodes, L1 is the entrance loop inductance, R is a resistance, C is a capacitor, V2 is the voltage load which represents the Electromotive Force (EMF) of a DC motor or the voltage value of a Battery in the case of a battery charge application, I_{L1} and I_{L2} are the currents which flow through inductors L1 and L2 respectively, δ is the duty cycle.

Figure 2 and Figure 3 show how the 4PDS works to switch from circuit 1 to circuit 2 in order to reach the Luo-converter circuit topology for operation in *Quadrants I, II and III, IV* respectively.

The circuit can work in four modes or quadrants as follows:

1. Mode A (Quadrant I): Forward acceleration.
2. Mode B (Quadrant II): Brake in forward operation.
3. Mode C (Quadrant III): Reverse acceleration.
4. Mode D (Quadrant IV): Brake in reverse operation.

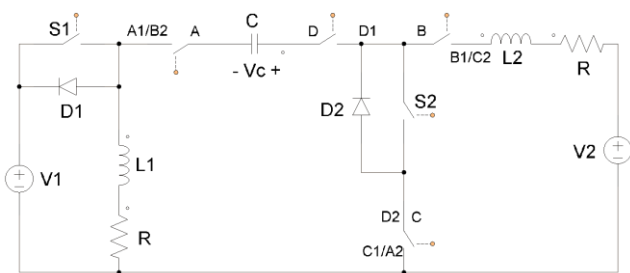


Figure 1. Combined Luo-converter circuit topology with a 4PDS switch.

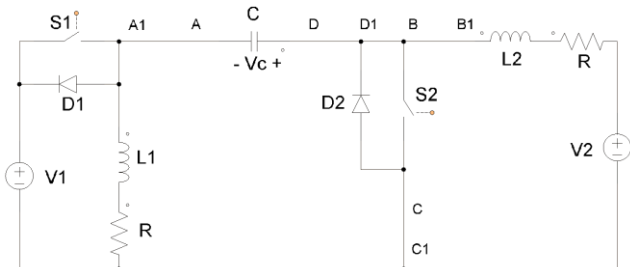


Figure 2. Luo-converter circuit topology for Quadrants I and II

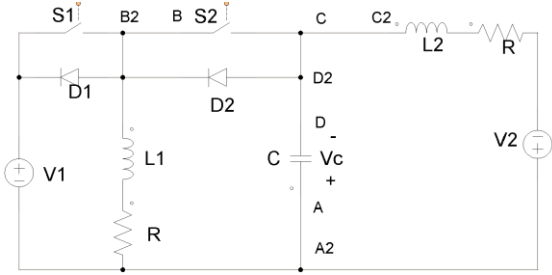


Figure 3. Luo-converter circuit topology for Quadrants III and IV

For a comprehensive review of the functionality of these circuits, as explained by Luo and Hong Ye, refer to (Luo & Ye, Chapter 7 - Multiple quadrant operating Luo-Converters, 2003) (Luo, Ye, & Rashid, Four quadrant operating Luo-Converters, 2000).

Table 1 shows the operation mode of the circuit depending on the 4PDS and the states of switches S1 and S2.

The considered parameters for the circuit based on calculations in (Luo & Ye, Chapter 7 - Multiple quadrant operating Luo-Converters, 2003) (Luo, Ye, & Rashid, Four quadrant operating Luo-Converters, 2000) are: $V1 = 42 [V]$, $V2 = \pm 14 [V]$, $R = 0,05 [\Omega]$, $L1 = L2 = 0,5 [mH]$, $C = 20 [\mu F]$ and $f = 50 [kHz]$. Polarity of V2 depends on the mode of operation (+) for Modes A & B and (-) for Modes C & D.

Table 1. Modes of operation

Mode	S1	S2	4PDS
A (Quadrant I)	PWM switching	Off	Pin A connected to pin A1 Pin B connected to pin B1 Pin C connected to pin C1 Pin D connected to pin D1
B (Quadrant II)	Off	PWM switching	Pin A connected to pin A1 Pin B connected to pin B1 Pin C connected to pin C1 Pin D connected to pin D1
C (Quadrant III)	PWM switching	Off	Pin A connected to pin A2 Pin B connected to pin B2 Pin C connected to pin C2 Pin D connected to pin D2
D (Quadrant IV)	Off	PWM switching	Pin A connected to pin A2 Pin B connected to pin B2 Pin C connected to pin C2 Pin D connected to pin D2

3. SIMULATION RESULTS

3.1 Current behaviour for a $\pm V2$ load.

If V2 is positive and current $IL2$ is increased positively, it means that the circuit is trying to get the acceleration state. Furthermore, if V2 is positive and the current $IL2$ is increased negatively, then it determines a positive braking mode.

For negative acceleration state, V2 is negative and also the current $IL2$ is increased negatively and negative braking state is determined by a negative V2 with positively increasing of $IL2$.

3.2 Current behaviour for a DC motor load.

As shown in Figure 4, a DC motor is implemented as a load in the output where V_e represents the separately excitation

voltage for the motor. Table 2 shows the motor parameters considered in the implementation.

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Where, R_a is the Armature resistance, L_a is the Armature inductance, R_f is the field resistance, L_f is the field inductance, V_t is the Nominal voltage, I_a is the nominal current, n is the nominal speed.

Figure 5 shows the motor speed and the current in the output I_{L2} in acceleration and braking modes with a DC motor load. In purple it shown the motor speed that defines positive acceleration in Figure 5a, brakes positively as shown in Figure 5b, accelerates negatively as shown in Figure 5c and brakes negatively as shown in Figure 5d. Braking is started in $t=0.4$ because it depends on acceleration state.

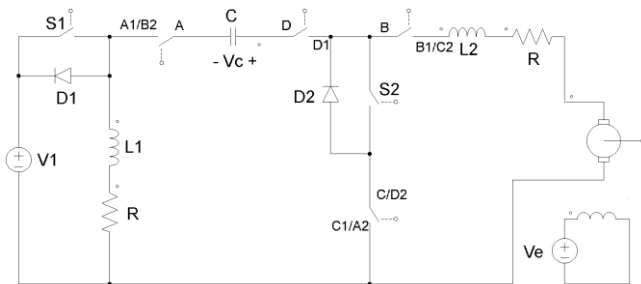


Figure 4. Combined Luo-converter circuit with a separately excited DC motor load

Table 2. DC Motor parameters

Parameter	Value
R_a	0,7 [Ω]
L_a	10 [mH]
R_f	75 [Ω]
L_f	20 [mH]
Moment Inertia	0,7 [kgm ²]
V_t	120 [V]
I_a	10 [A]
n	500 [rpm]
I_f	1,6 [A]
V_e	120 [V]

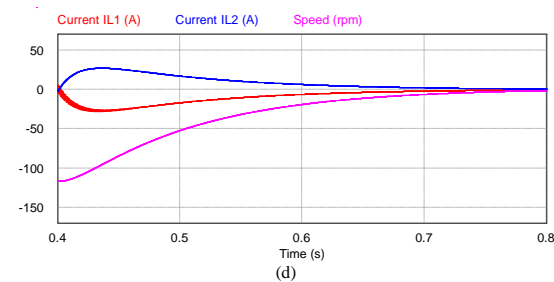
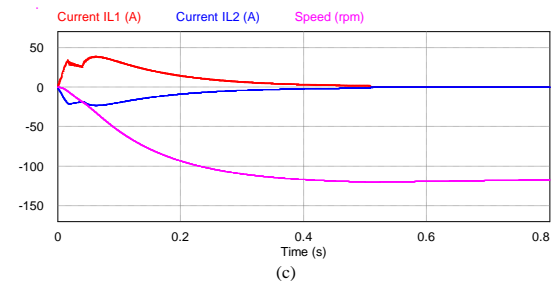
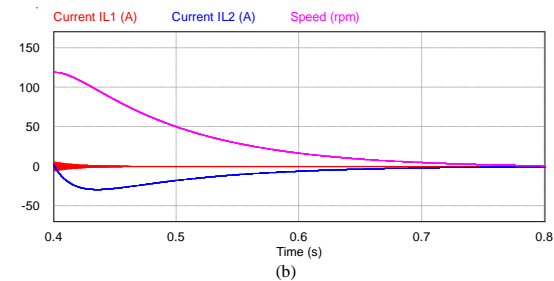
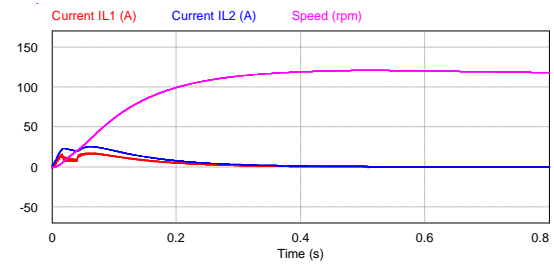


Figure 5. Speed output for a (a) motor load with $\delta = 0,40$ (Mode A), (b) motor load with $\delta = 0,99$ (Mode B) at $t=0,4$, (c) motor load with $\delta = 0,40$ (Mode C), (d) motor load with $\delta = 0,99$ (Mode D) at $t=0,4$ (Powersim, 2016).

Duty cycle values were tested in the experimentation in order to obtain safe operation ranges. It was necessary because overcurrent values could damage the circuit and small values can make the circuit to respond extremely slow, then, the safe duty cycle range was between, $0,30 < \delta < 0,50$ for acceleration modes and $0,80 < \delta < 0,99$ for braking modes.

4. CONCLUSIONS

The proposed combined circuit model for a four-quadrant operation Luo-converter seems to be reliable for controlling a DC motor load in acceleration and braking modes. This is possible due to EMF, as a generating part of the output current increase positively or negatively depending on the operation mode.

The considered parameters for a DC motor make the circuit more reliable for a future implementation considering safe duty cycle ranges in order to protect the circuit integrity and

stability. These ranges are, $0,30 < \delta < 0,50$ for acceleration modes and $0,80 < \delta < 0,99$ for braking modes.

It is important to consider maximum current values when suddenly changing quadrants, as these could damage circuit elements, e.g. a change from I quadrant to III quadrant over increases the input loop current.

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BIOGRAFÍAS



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