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Novel Design of the Converter for an Active UPS Application Based on Marx Modulator Concept with Supercapacitors

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Abstract. A new Marx modulator 4-leg multilevel converter is proposed to replace the well-known 4-leg inverter fed from batteries in Uninterruptible Power Supply (UPS) applications. The novel design concept for the Marx modulator based multilevel converter is presented and described. Each leg uses 2 Marx modulator modules, each one using an Electrochemical Double-Layer Capacitor (EDLC) (also known as supercapacitor (SC)) energy storage bank. The new topology concept enables multilevel operation with five voltage level per phase, allowing high quality voltage and current waveforms, distributed supercapacitor storage and reduction of supercapacitor bank voltage. The proposed converter can operate as UPS or as Active Power Filter (APF), powering non-linear or/and unbalanced loads, while balancing each leg supercapacitor voltage. A control strategy to choose the redundant vector configuration to balance the supercapacitor voltages is explained. Simulation results are presented for a Marx modulator based interactive 40kVA UPS.

Keywords: Uninterruptible Power Supply, supercapacitors, bipolar Marx modulator multilevel converter.

1 Introduction

Nowadays, electrical power quality is a concern for customers with loads that are sensitive to the quality of the voltage waveform and are responsible to immunizing their own facilities. The electrical distribution is often subject to grid distortion in terms of periods of variation and intensity (non-linear loads, etc.). However, some critical loads need a stable voltage supply and higher quality than the transmission

and distribution network operators can satisfy. Although the less expensive methods to achieve protection against some power problems, none of them can reasonably isolate the system from power supply problems as well as good uninterruptible power supply (UPS).

UPSs are systems that are developed to supply sensitive loads such as telecommunication systems, computer sets, hospital equipment or production lines in the manufacturer industries [1], when there are disturbances in the electrical network for a limited period. UPS can also correct other network events such as overvoltage, voltage variations, noise, frequency instability or harmonic distortion. UPS differentiate themselves from other emergency systems by enabling instantaneous power supply when a power outage occurs in the network through electronic circuits associated with energy storage systems, such as flywheel for high power systems or batteries, and supercapacitors for low power systems, [2, 3]. For all these storage systems, it is necessary to use electronic power converters. In the case of a low-power UPS, the classic solution consists of the use of a DC-DC converter and a 4-leg inverter and a bank of batteries or supercapacitors (SC). In the case of supercapacitors, they have a high lifetime of more than 500 thousand cycles with discharge cycles in the order of 100%. However, its low working voltage requires the use of series of supercapacitors for the required voltage. In this way, the use of supercapacitors in series brings with it the need of voltage equalization, to prevent overvoltage and possible damage of the supercapacitors, which can become unbearable.

Thus, the investigation of the issues associated with the use of modular converters with capacity to mitigate the problem of voltage equalization in supercapacitor banks is relevant. An alternative solution is the multilevel converter, [4, 5]. The applications indicated for multilevel converters range from the interface between high-voltage transmission networks to variable-speed drives for use in medium-power drive systems. Different multilevel conversion topologies are described in the literature, being the most studied and most used: the multilevel converter with diodes of connection to the neutral point; the multilevel flying capacitor converter and the multilevel converters of half-bridges and complete cascade bridges [6-13]. Cascade converters are modular, however, they require independent DC voltage sources making them expensive. There is reference to the use of the cascade bridge converter in high power applications demanding from the point of view of the quality of energy [14]. Considering the first two converters, it is necessary to control the converters to ensure a balanced distribution of the DC bus voltage across all capacitors. Most of the techniques used to balance the voltage in the capacitors use the redundant configurations from the point of view of the output AC voltages, but they are different in relation to the current flows in the DC bus. Proper selection of the redundant configuration allows the equalization of the voltages in the capacitors to be achieved. This requirement increases the complexity of the control of the system, especially for a number of levels greater than 3, which may prevent the smooth functioning of the multilevel converter. Thus, it is current and fundamental to investigate new topologies of modulator converters, for issues associated with voltage equalization in supercapacitors bank, and in particular the topology of the Bipolar Marx Generator (BMG), [15-21].

The topology of the BMG is a modular circuit and it's largely used in the Pulsed Power field, which uses a switching system to charge a set *n* of capacitors in parallel from a DC voltage source, with a reduced amplitude and produces transiently a voltage whose amplitude approaches a multiple of the input DC voltage value. Thus, due to the characteristic of charging the capacitors in parallel, it is relevant to study the topology of the BMG to mitigate the voltage equalization problem in supercapacitors banks, under the UPS application. Due to the modularity characteristic of the BMG topology, the proper selection of the redundant configuration in terms of the output voltage can further contribute to achieve the equilibrium of supercapacitors bank voltages.

This paper presents the preliminary simulation results of a novel proposal for the Marx based converter for an active type UPS (Fig. 1), to minimize the impact of the voltage equalization between the set of supercapacitors bank.

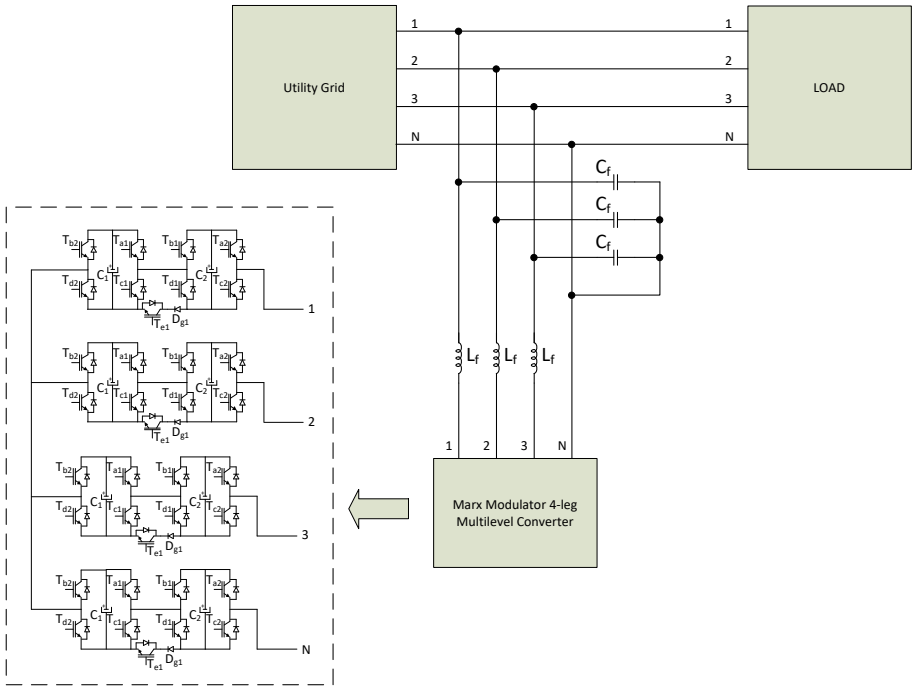


Fig 1. General scheme of an active UPS.

Considering the general scheme of an active UPS represented in Fig. 1, the storage system/converter part consist in 4-leg Marx modulator multilevel converter as represented also in Fig. 1, and an output L_fC_f filter due to the distorted pulse-width-modulated (PWM) waveform generated by the converter.

2 Relationship to Industrial and Service Systems

In an increasingly competitive society focused on the value generation for customers through innovative business models instead of merely selling products, and namely for applications with sensitive loads needing UPS such as telecommunication systems, computer sets or hospital equipment's, the study of different type of approach in terms of the converter, is relevant.

In this paper we present a bipolar Marx multilevel converter with supercapacitors, which can operate as a UPS or as APF, powering non-linear or/and unbalanced loads, while generating 5 voltage level per phase and allowing high quality voltage and currents waveforms with distributed supercapacitor storage and reduction of supercapacitor bank voltage.

3 Circuit Operation

Considering the circuit of Fig. 1, each converter leg has one solid state bipolar Marx modulator with two stages. Thus, it is considered only one converter leg to explain the circuit operation as UPS and as an active filter, as represented in Fig. 2.

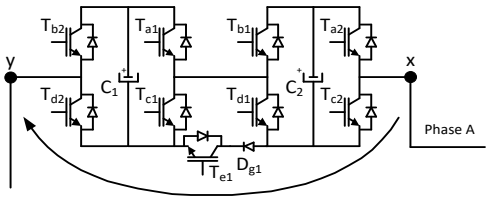


Fig. 2. Bipolar Marx modulator of the storage/converter system.

Fig. 2 shows the proposal topology of the converter based on Marx concept with two modules, capable of delivering repetitive bipolar output voltage to different types of load, using insulated gate bipolar transistor (IGBTs) as ON–OFF switches. Each module consists in 4 switches T_{ai}, T_{bi}, T_{ci} and T_{di} and one supercapacitor bank C_i, which consist of supercapacitors in series. The modules are interconnected through the switch T_{e1} and diode D_{g1}. The operating modes of the circuit presented in Fig. 2 are described in the following sections both as UPS and as an active filter.

The circuit of Fig. 2 allows different paths to generate different levels of voltage. Considering that the supercapacitor banks C_1 and C_2 are equally charged and $U_{C1}=U_{C2}=Us/2$, and for instance, if a (+Us/2) voltage level is needed between XY, switches T_{d2}, T_{a1}, T_{d1} and T_{c2} (or switches T_{d2}, T_{a1}, and T_{b1} and T_{a2}) are turned ON and all others are OFF, using the supercapacitor bank C_1. Another path can be considered, using the supercapacitor bank C_2 voltage through the switches T_{a2}, T_{d1}, and T_{c1}, T_{d2} (or switches T_{a2}, T_{d1}, and T_{a1} and T_{b2}), as represented in Table 1. Other output voltage levels paths are summarized in Table 1.

Table 1. Semiconductors in On-state driven for different operating modes of the circuit of Fig.3

XY Output Voltage	Path	SC Bank Used
$+U_S$	T_{a1}, T_{d1}, T_{a2}, T_{b2}	C_1 and C_2
$+U_S/2$	T_{d2}, T_{a1} and [(T_{d1}, T_{c2}) or (T_{b1}, T_{a2})] or T_{a2}, T_{d1} and [(T_{c1}, T_{d2}) or (T_{a1}, T_{b2})]	C_1 or C_2
0	T_{c1}, T_{d2} and [(T_{d1}, T_{c2}) or (T_{b1}, T_{a2})] or T_{a1}, T_{b2} and [(T_{b1}, T_{a2}) or (T_{d1}, T_{c2})] or (T_{a1}, T_{d2}, T_{b1}, T_{c2}) or (T_{a1}, T_{d2}, T_{d1}, T_{a2})	- - (C_1-C_2) or (-C_1+C_2)
$-U_S/2$	T_{b2}, T_{c1} and [(T_{d1}, T_{c2}) or (T_{b1}, T_{a2})] or T_{c2}, T_{b1} and [(T_{c1}, T_{d2}) or (T_{a1}, T_{b2})]	C_1 or C_2
$-U_S$	T_{c1}, T_{b1}, T_{c2}, T_{b2}	C_1 and C_2

Besides the five levels of voltage described under Table 1, the topology of the Fig. 2 allows the equalization of the voltages between the supercapacitor banks C_1 and C_2, and only from C_1 to C_2 through the path of switches T_{a1} and T_{e1} and antiparallel diode of switch T_{b1} and diode D_{g1}.

3.1 Control Strategy

The converter is controlled in order to achieve the predefined technical goals: control AC load voltages, when in UPS operating mode and achieve sinusoidal grid currents, when in active filter operating mode. For this purpose, the AC current control is the first control loop. Fig. 3 shows a block diagram of this control loop. The converter output phase currents are controlled using a sliding mode hysteretic controller, with reference signals given by the phase current dq components references.

Chosen the output voltage to be applied by the converter, the switching path is now selected between the available redundant configurations. The switching path is chosen, using a cost function which leads to the minimum error between the SC voltage and the reference that is previously stablished.

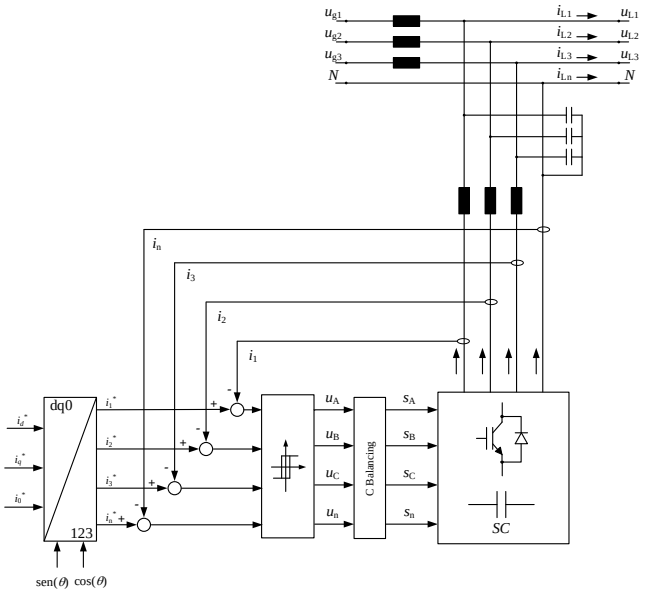


Fig. 3. General control diagram of the storage/converter system.

Upon current control loop, other controllers may be designed according to the system functions, such as: output AC voltage control for UPS standalone operation; active filtering and reactive power control and U_{dc} voltage control in respect to SC charge.

3.2 UPS Operating Mode

Under UPS operating mode, it is considered that all banks of supercapacitors are charged with Us/2. Thus, when a failure in the utility grid is detected, the grid is disconnected, and the system starts the operation of the BMG converters to supply the load in standalone, from the point the grid was interrupted once the controller is synchronous with the utility grid.

The converter output current components dq0 references are obtained from a predictive approach to control the load voltages [22], Fig. 4 a).

3.3 Active Power Filter Operating Mode

When in active filter operating mode, the main goal is to obtain sinusoidal current in the grid phases with almost unity input power factor. The converter supplies the total reactive and deformation power to the load and the grid provide only the fundamental component. In this operating mode, the converter output current components dq0 references are obtained extracting the average value of the fundamental component from the load currents [23, 24], Fig. 4 b).

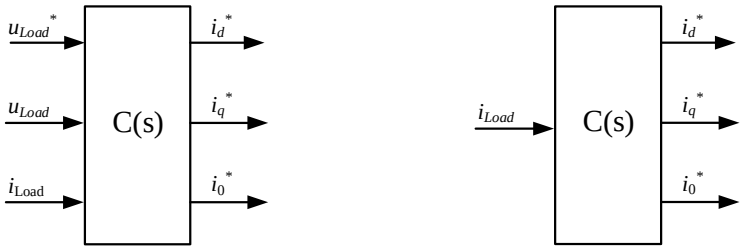
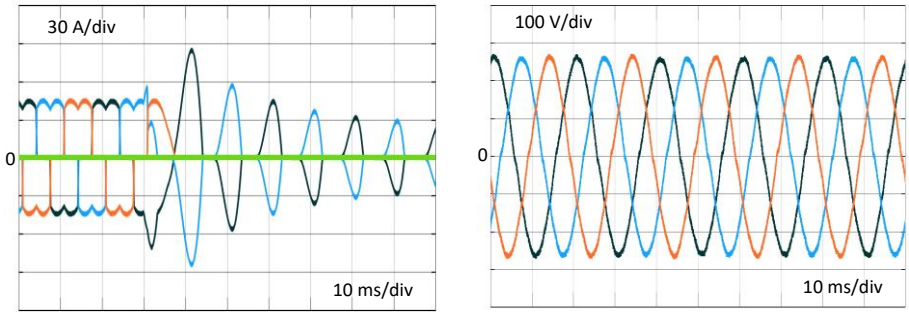


Fig. 4. Converter output current components dq0 references to control the: (a) load voltages in UPS operating mode; and (b) load currents in filter operating mode

4 Simulation Results

The circuit of Fig. 1 was simulated using Matlab/Simulink software. The equivalent capacitance of each supercapacitor bank is 2F. The parameters of the L_fC_f filter are 600mH and 5.6μF respectively. The circuit of Fig. 1 was simulated as UPS (Fig. 5) and as APF (Fig. 7), powering non-linear or/and unbalanced loads. It was considered to show the simulation results for the worst load case, which is a non-linear and unbalanced load.

In Fig. 5 it is presented the simulations results for the current and voltage waveforms into a non-linear unbalanced load. Under this situation, the load was changed from linear to non-linear unbalanced load.



(a) (b)

Fig. 5. Simulation results of the (a) current and (b) voltage waveforms of the circuit of Fig. 1 operating as UPS and with a non-linear unbalanced load. The scales are 10ms/div (horizontal) and (a) 30A/div (vertical) and (b) 100V/div (vertical).

Considering the simulations results as UPS operating mode (Fig. 5) the load voltage follows the three-phase voltages references for a non-linear and non-balanced load.

Fig. 6 shows the voltages waveforms of two SC banks of one converter leg when operating as UPS and powering linear and non-linear or/and balanced and unbalanced loads. The results show that the controller strategy used can balance the SC banks voltage of each converter leg.

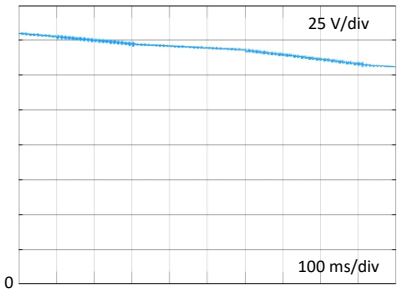
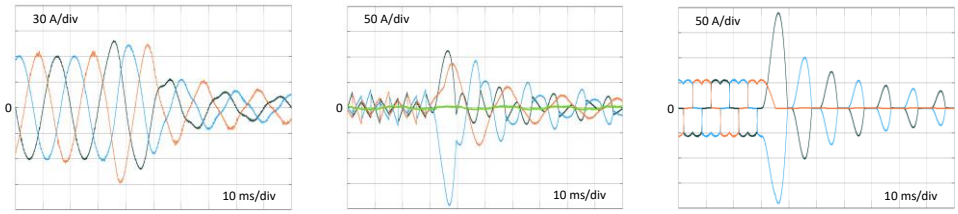


Fig. 6. Simulation results of the voltage waveforms in supercapacitor banks of the Marx modulator 4-leg multilevel converter, operating with linear and non-linear or/and balanced and unbalanced loads. The scales are 100ms/div (horizontal) and 25V/div (vertical).

Considering the active filter operating mode, Fig. 7 shows the current waveforms in the utility grid, the output currents of the Marx modulator 4-leg multilevel converter and the load currents, when operating with non-linear unbalanced load.



(a) (b) (c)

Fig. 7. Simulation results of the circuit of Fig. 1 operating as APF, for currents in utility grid (a), output currents of the Marx modulator 4-leg multilevel converter (b) and currents into non-linear unbalanced load (c). The scales are 10ms/div (horizontal) and 30A/div (vertical) and 50A/div (vertical).

Considering the simulation results presented in Fig. 7, when the converter is in APF operation mode it can be seen that the converter imposes a three-phase balanced sinusoidal currents in the power grid, under non-linear unbalanced load condition.

5 Conclusion

A new design method for the converter for an active type UPS (Fig. 1) application, is proposed. The proposed concept allows the distribution of the energy necessary to supply the load along the converter legs. Yet, the modular characteristic of the Marx modulator converter allows to distribute the energy of each converter leg in equal parts as a function of the number of stages. Thus, the higher number of stages, the lower hold-off voltage of the supercapacitors bank. Also, the increase of the number

of the stages in Marx modulator, allows to perform more levels which can allow to increase the electrical power quality.

Simulation results shows that the Marx based converter of the circuit of Fig. 1, with 2 stages in each converter leg, can produce a three-phase sinusoidal voltage into a linear and non-linear or/and balanced and unbalanced load. Also, the simulation results show that the waveforms of the voltages between supercapacitor banks of each converter leg have similar progress, due to the implemented controller that can choose the best redundant configuration that fits to a specific moment.

Under the active filter operating mode, the simulation results show that the system provides the correction of the currents of the utility grid.

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