A ZCZVS PWM THREE LEVEL FULL BRIDGE McMURRAY INVERTER USING AN AUXILIARY POWER SUPPLY TO CONTROL SYSTEM

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***Abstract* – This paper proposes a PWM inverter that allows the main switches to be turned on and off at zero voltage and zero current with controlled di/dt and dv/dt rates. The reverse recovery losses of the main diodes are minimized, and the auxiliary switches are turned on and off in a ZCS mode. The main switches turning-on at zero current can reduce significantly the undesirable effects of the parasitic inductances related to the circuit layout. The commutation losses are practically reduced to zero and the EMI emission can also be minimized. The operation of the ZCZVS PWM Full-Bridge McMurray, using an auxiliary power supply to the control system, is analyzed, and design guidelines for the auxiliary commutation cell are recommended based on this analysis. Experimental results are presented to demonstrate the feasibility of the proposed 2kW inverter.**

KEYWORDS

UPS, ZCZVS, Full Bridge McMurray inverter,.

I. INTRODUCTION

The purpose of zero-current-transition (ZCT) is to force the current flowing through a device to decrease to zero before this device is turned on or off. This is accomplished by the addition of an auxiliary circuit that provides a resonant current to take away the current flowing through the main device before the switching transition. With the ZCT techniques, inverters are expected to achieve a higher switching frequency with reduced switching losses, attenuated acoustic noise, and reduced electromagnetic interference (EMI).

Figure 1 shows a typical three-phase ZCT inverter circuit. Historically, the research with this circuit configuration goes back to the McMurray inverters for the SCR forced current commutation [1]-[2]. For the soft transition research with modern gate-turn-off devices, such as IGBTs, several ZCT control schemes were developed to achieve the zero-current turn-off [3,4]. Recently, still with the same circuit, a new ZCT scheme was proposed, which improves the performance by enabling both the main switches and auxiliary ones to be turned on and off under zero-current conditions, and achieving a near-zero-voltage turn-on for the main switches [5] [6]. As a result, besides the elimination of switching turn-off loss, the diode reverse recovery current and the switching turn-on loss are also substantially reduced, the distribution of current and thermal stresses in the auxiliary switches is evened out, and the resonant capacitor voltage stress is reduced by 30%. In order to provide guidelines for the scheme proposed in [5] and [6], which realizes the zero-current and near-zero-voltage switching in high power applications, this paper presents the design considerations through a study example of a 2 kW three-phase prototype inverter. For consistency, the inverter designed is still called a ZCT inverter.

This paper first explains principles of the soft-transition scheme. Then, it investigates key aspects of the inverter design, including determination of the resonant tank parameters, design of the resonant inductor, selection of the resonant capacitor, and selection of the auxiliary switches. A new method of testing devices under the zero current switching condition is proposed to select eligible auxiliary switches. Design of the inverter layout is also addressed. Trade-off issues are discussed. The 2 kW inverter has been completely implemented and tested to the full power level with a closed-loop controlled induction motor drive system. Experimental results are provided to verify the design guidelines.

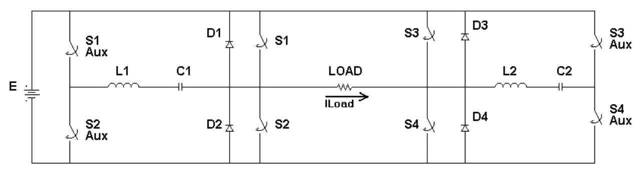


Figure 1 – Three-phase ZCT inverter circuit.

II. PRINCIPLE OF OPERATION

A - The ZCZVT PWM Full-Bridge McMurray Inverter

Figure 2 shows the ZCZVT PWM Full-Bridge McMurray inverter with the auxiliary self-oscillating power supply. It differs from a hard-switching PWM Full-Bridge inverter by the presence of additional auxiliary switches *S1aux* and *S2aux* and a shunt resonant network composed of two resonant capacitors *C1* and *C2*, and also two resonant inductors *L1* and *L2*.

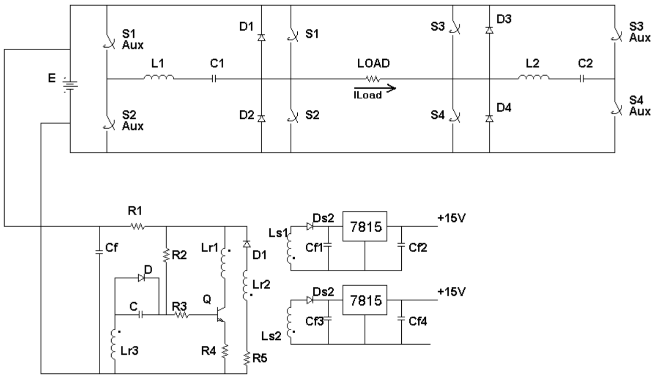


Figure 2 – Full-Bridge McMurray inverter with an auxiliary power supply.

B - Operating Principles

To simplify the analysis, the output current I_{Load} is considered constant within a switching cycle. The operation of the auxiliary commutation circuit is valid for the cases where I_{Load}<0 and I_{Load}>0. The operating principles will be explained for a single case only, i.e. commutations from *D2-D3* to *S1-S4*, and from *S1-S4* to *D2-D3*. As shown in Figure 3, there are ten operating stages along a switching cycle, which are described as follows. The circuit operation for the cases where I_{Load}>0 and I_{Laod}<0 are symmetrical. Therefore the operatiog principle analysis is summarized, referring to I_{Load}>0, where the waveforms are shown in Figure 4.

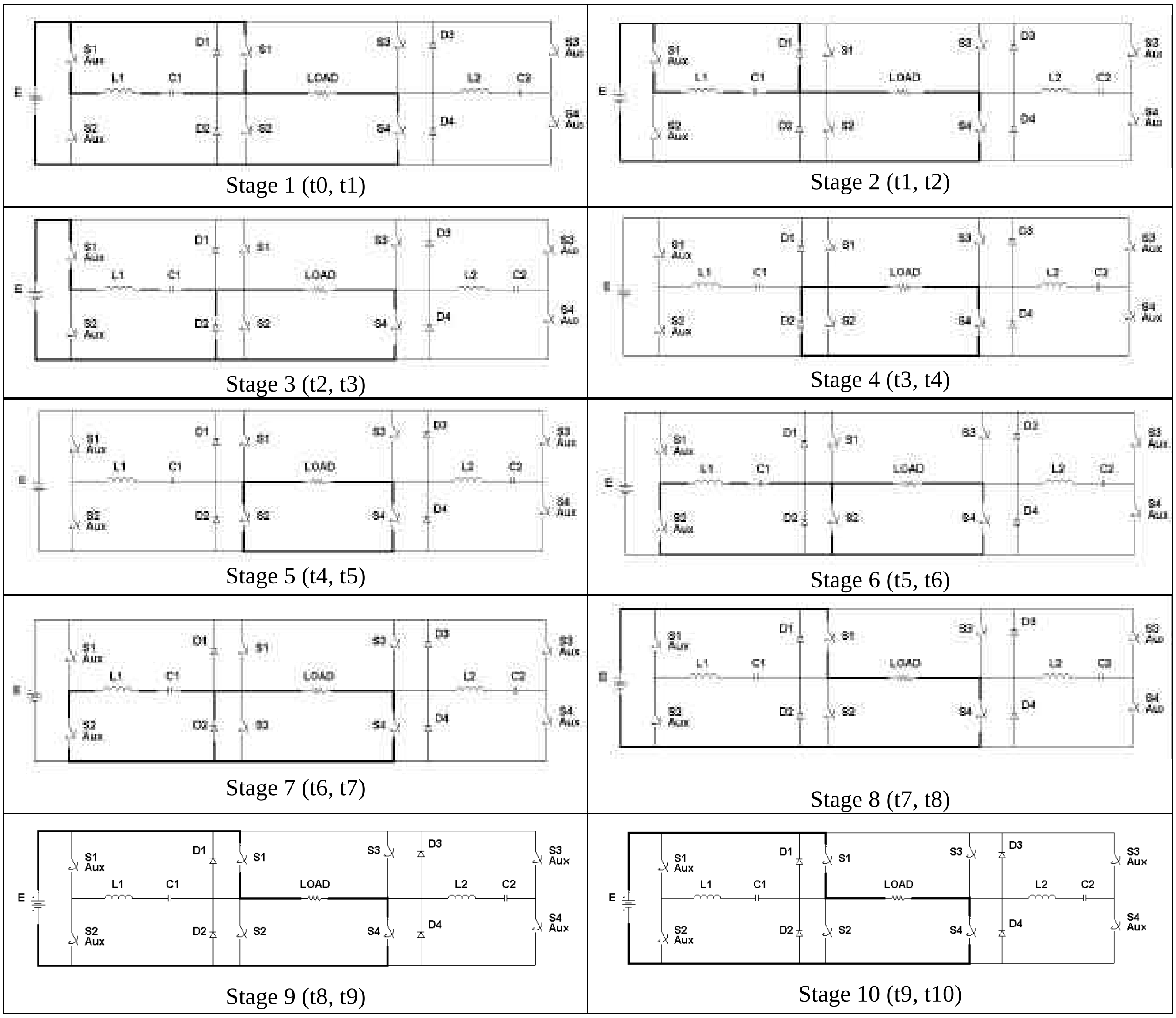


Figure 3 – Operating stages.

a) Turn-On Transition [*t0, t4*]: The turn-on process relies on the initial voltage across the resonant capacitor. When *S1aux* is turned on at *t0,* the resonant current I_x increases in the negative direction to a peak and then decreases to zero at *t1*. After *t1*, current I_x reverses its direction in which diode *D1* conducts, and *S1* is turned off at the zero-current condition. At *t2*, I_x rises to I_{Load}, and the current in *D2* drops to zero. Since switch S1 is still off, I_{Load} can flow only through the resonant tank, charging *C1* linearly. There is a voltage difference between V_{dc} and V_x. The voltage across switch *S1* equals this difference and thus is less than *Vdc*. At *t3*, S1 is turned on with the zero-current and near zero-voltage condition. The gate driver signal of the bottom main switch *S2* should be removed before *t1*.
b) Switch-On Stage [*t4, t5*]: At *t4*, I_x drops to zero, and *D1* is turned off naturally. I_{Load} flows through switch *S1*, and the PWM operation resumes. The resonant capacitor maintains a negative voltage, which is less than V_{dc}.
c) Turn-Off Transition [*t5, t10*]: Before *S1* is turned off, *S2aux* is turned on at *t5*. The capacitor voltage establishes a resonant current I_x flowing in the positive direction. After *t6*, I_x exceeds I_{Load}, the current in switch *S1* drops to zero, and diode *D1* starts to conduct the surplus current. I_x increases to a peak and then drops to I_{Load} at *t7*. *S1* is turned off at the zero-current condition, and its gate driver signal is removed between *t6* and *t7* without causing turn-off loss. After *t7*, V_{dc} is included in the resonant path. Since diode *D2* is still reverse biased, I_{Load} can flow only through the resonant tank, charging *C1* linearly. At *t8*, V_x exceeds V_{dc}. Thus, diode *D2* becomes forward biased and starts to conduct. *L1* and *C1* start to resonate again. When I_x swings back to zero at *t9*, diode *D2* starts to conduct. *S2* is turned off under the zero-current condition. The gate driver signal of the bottom main switch *S2* can be applied after *t8*.
d) Diode-On Stage [after t10]: I_x returns to zero at *t10*. *D1* is turned off naturally, I_{Load} flows through diode *D2*, and the PWM operation resumes.

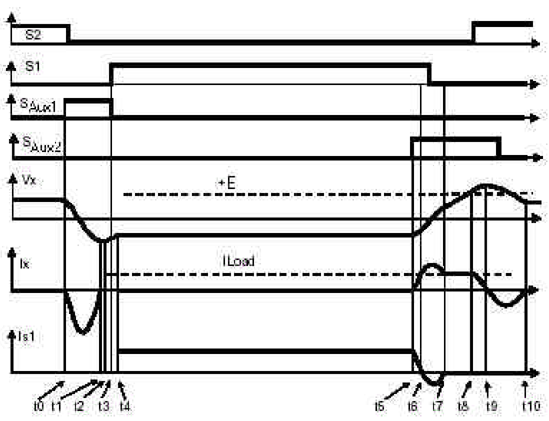


Figure 4 – Theoretical waveforms.

III. DESIGN EXAMPLE

This section presents a design procedure and an example to determine the values regarding the resonant tank elements of the proposed ZCZVT commutation for the proposed McMurray inverter. The given specifications are presented in Table I.

Table I – Design specifications.

Parameter	Value
Output Power	Po=2000W
Input Voltage	E=400V
Output Voltage	Vo=220Vrms
Output frequency	fo=60Hz

The design procedure consists of four steps, as follows.

a) Calculation of the output current peak, given by (1).

$$I_0 = \frac{\sqrt{2}P_0}{V_0}(1+ \quad I) \tag{1}$$

(b) Calculation of the characteristic impedance. To assure the main switches turning-off under ZCS and ZVS conditions, during stages 9 and 10, the peak current taken away from the main switch to the auxiliary circuit must be larger than the output current peak. From these stages, the current peak through capacitor Cr_2 is given by:

$$I_{pk} = \frac{E}{\sqrt{2}Z_0} \tag{2}$$

From (1) and (2), a new parameter *k* can be defined as follows:

$$k = \frac{I_{pk}}{I_0} \tag{3}$$

where k 1.

If k=1 is adopted, which is a practical design value to compensate the parasitic losses, the characteristic impedance Z_0 can be given by:

$$Z_0 = \frac{E}{\sqrt{2}kI_0} \tag{4}$$

c) Calculation of the resonant frequency. To minimize the reverse recovery of the main diodes, the resonant frequency in stage 2 can be chosen to control the di/dt rate during turn-off, which is then given by (5).

$$\frac{di}{dt} \quad \frac{I_0 w}{\sqrt{2}\sin^{-1}\left(\frac{1}{2k}\right)} \tag{5}$$

The resonant frequency can be obtained from (5) as follows:

$$w = \frac{\frac{di}{dt}\sqrt{2}\sin^{-1}\left(\frac{1}{2k}\right)}{I_0} \tag{6}$$

d) Calculation of the resonant components. If the characteristic impedance and the resonant frequency are given, expressions (7) and (8) can be used to calculate the resonant inductor and capacitor.

$$L1 = L2 = \frac{Z_0}{w} \tag{7}$$

$$C1 = C2 = \frac{1}{Z_0 w} \tag{8}$$

If a di/dt rate equal to 80A/µs [4] is adopted, the resonant components values *L1*, *C1*, *L2* and *C2* can be calculated for both legs of the converter, where the first one operates at 30kHz and the second one operates at 60Hz, as shown in Table II.

Table II – Design example.

Parameter	Value
I_0	15.4A
Z_0	15.3Ohms
L1	5.2 H
C1	17.4nF
L2	2.6 H
C2	7.2nF

IV. CONTROL STRATEGY

The control strategy employed in the proposed inverter is called complementary modulation, which provides nearly sinusoidal current and voltage waveforms. Therefore the sinusoidal shape is guaranteed for any type of load i.e. inductive or capacitive loads. The principle of this control scheme is shown in Figure 5, where the complementary modulation is depicted. The complementary modulation is necessary since the output current is not in phase with the output voltage, and it is defined as a function of the load, therefore imposing the sinusoidal waveforms to both voltage and current.

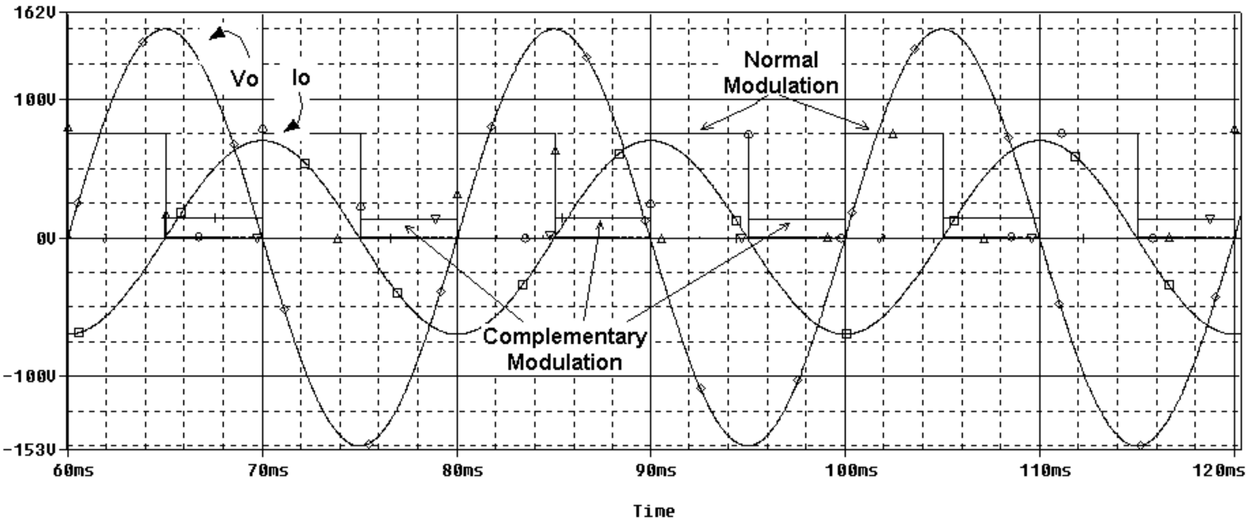


Figure 5 – Control strategy using complementary modulation.

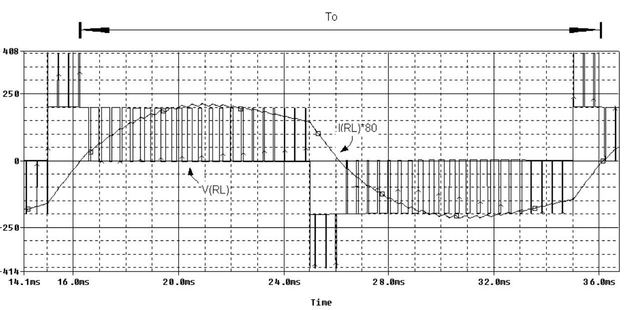
V. SIMULATION RESULTS

In order to illustrate the operation of the converter, simulation and experimental tests were carried out as the parameter set shown in Table III was employed.

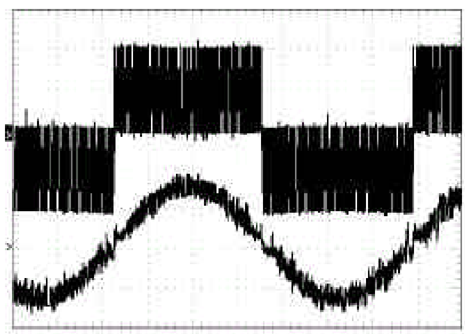
Simulation results are shown in Figure 6, and experimental ones are shown in Figure 7.

Table III – Parameter set employed in simulation and experimental tests.

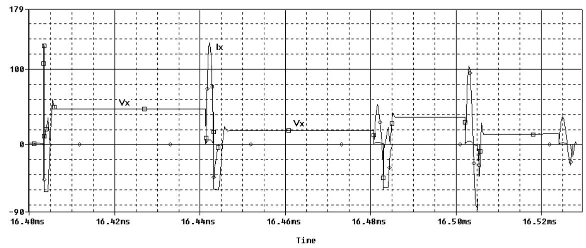
E=400V;	f_S=30 kHz	V_0=220Vrms;
C1=17.4nF;	L1=5.2 H;	f_0=60Hz;
C2=7.2uF;	L2=2.6mH;	P_0=2000W;



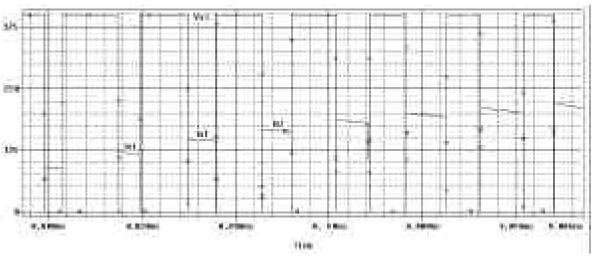
(a) Output voltage (40V/div) and output current (0.2A/div).



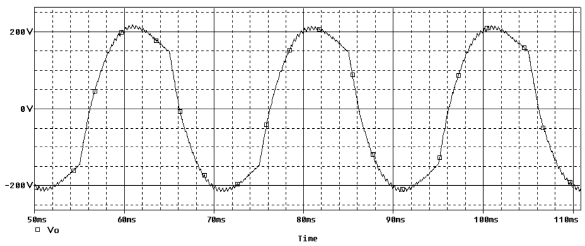
(a) Output voltage (50V/div) and output current (0.2A/div).



(b) Voltage (20V/div) and current (0.2A/div) waveforms through resonant capacitor and resonant inductor.

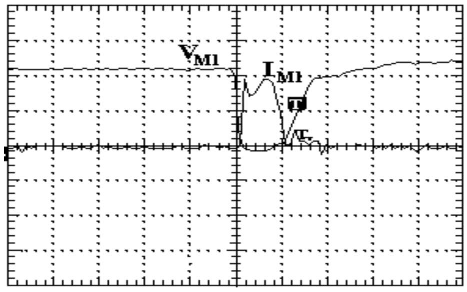


(c) Drain-source voltage (25V/div) and current (0.4A/div) waveforms in switch S1.

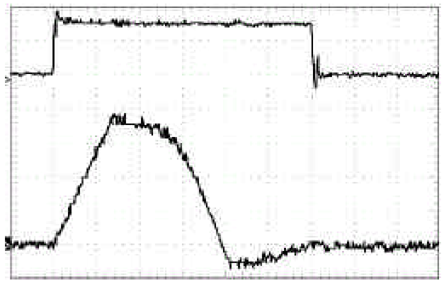


(d) Output voltage (50V/div).

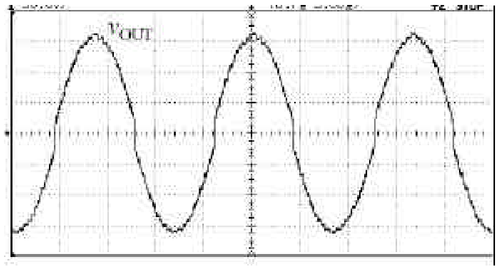
Figure 6 – Simulation results of the DC-AC Full-Bridge Mcmurray Inverter converter using a non-dissipative snubber.



(b) Voltage (50V/div) and current (0.2A/div) waveforms through resonant capacitor and resonant inductor.



(c) Drain-source voltage (100V/div) and current (0.4A/div) waveforms in switch S1.



(d) Output voltage (50V/div).

Figure 7 – Experimental results of the DC-AC Full-Bridge Mcmurray Inverter converter using a non-dissipative snubber.

VI – CONCLUSION

This work presents an active auxiliary commutation topology for a three-level PWM ZCZVS Full-Bridge Mcmurray Inverter, based on the resonance principle. The auxiliary circuit is bi-directional, operating at ZVS and ZCS conditions.

It is important to mention that the proposed inverter consists in a three-level topology without the need of auxiliary supplies, differently of some counterparts. The proposed circuit assures the soft switching of the main devices to any type of load i.e. inductive or capacitive loads, with low current stress and high efficiency.

The operation and performance are evaluated by simulation tests, which confirm the soft switching commutation in ZVS and ZCS ways for all the switches. Experimental results are also presented, which are compared to the simulation ones.

VII – ACKNOWLEDGMENT

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