A NEW HIGH FREQUENCY, ZERO-VOLTAGE SWITCHED, PWM CONVERTER

Ionel Dan Jitaru

ITT PowerSystem Corporation
Tucson, Arizona

In co-operation with Polytechnical
Institute of Bucharest
Bucharest Romania

ABSTRACT

A high efficiency, high power density converter, operating at constant frequency and switching at zero voltage is presented. Zero voltage switching conditions are achieved over a broad input voltage and output current range. Continuous power transfer from the input to the output minimizes the output filter requirements and by using integrated magnetics technique, high power density can be achieved. By employing the same configuration to classical PWM topologies, a new family of ZVS-PWM converters can be derived. An experimental 5V, 100Amp converter was designed and built. The converter operates from an input voltage of 200 to 430 Vdc, at 400Khz switching frequency.

INTRODUCTION

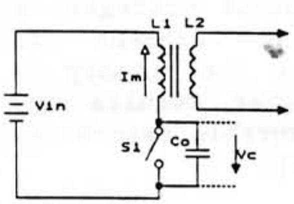
A common trend in the power supply industry is the quest for higher power density and higher efficiency. A general solution to achieve higher volumetric efficiency is by increasing the switching frequency, which leads to size and weight reduction of the capacitive and magnetic components. In the "hard" switching mode of operation, higher frequency will result in higher switching losses and EMI. Therefore resonant-mode operation, which recently has become more popular for low switching losses at high frequencies, has an inherent disadvantage in its control through modulation in frequency. In the case of quasi-resonant topologies, which also have become popular in the last several years, the advantage of very low switching losses are offset by the current or voltage stress on the main switch. Recently there is a trend in power conversion , to merge PWM and quasi-resonant technologies, sometimes refered to as constant frequency with resonant transitions. The resonant transition converter combines the best of both, by allowing resonant switching, while the transfer of power is through pulse width modulation.

Several years ago O.D. Patterson, presented a full bridge phase shifted zero voltage switching converter [2]. The concept became very popular and constituted the subject of several papers. This power processing technique is suitable mostly for high power levels, where the complexity is not a significant penalty. At the same time the zero voltage switching conditions are not achieved for light loads. In order to obtain zero voltage conditions, especially for high output voltages, a supplementary inductive element is required in series with the primary or secondary winding. Better results are obtained by using a saturable reactor as an inductive element [5].

NEW FAMILY OF ZVS-PWM CONVERTERS

The base element of the constant frequency converter with resonant transitions, is the "resonant circuit with initial conditions" which is depicted in fig 1. The circuit is a constituent of most power train topologies. It is composed of a voltage source Vin, an inductive element L1 and a resonant capacitor Co. The initial conditions are defined by the current through the inductive element L1 flowing towards the input source and the voltage across the capacitive element Co.

This resonant circuit is characterized by the following three parameters: Zc, which is the characteristic impedance and is defined by the (1), Ω is the natural frequency defined by (2), and the initial phase ϕ, which characterizes the initial conditions (3). The behavior of this circuit is characterized by the equation (4) and (5). The expression (6) shows the required conditions to guarantee the zero voltage switching conditions for the switching elements. From (6) it is concluded that if Vc$\gg$2Vin, zero voltage switching is achieved regardless of Im amplitude. In the case where Vc$\ll$2Vin, which is desirable for minimizing the voltage stress across the switch, a certain amplitude for Im is required for zero voltage switching conditions. This expression is valid only under the condition that there is no current flowing into the secondary during the resonant transitions. In the case of a forward converter, there is a current flowing into the secondary after the voltage across the switch decays in the resonant manner under the the level of input voltage source. In order to achieve zero voltage switching conditions with a minimum



$$Z_c = \sqrt{\frac{L_1}{C_0}} \quad (1)$$

$$\Omega = \frac{1}{\sqrt{L_1 C_0}} \quad (2)$$

$$\phi = \arctan\left[Zc \frac{I_m}{V_c - V_{in}} \right] \quad (3)$$

$$V_c(t) = V_c - (V_c - V_{in}) \frac{\cos \varnothing - \cos(\varnothing + \Omega t)}{\cos \varnothing} \quad (4)$$

$$I_m(t) = (V_c - V_{in}) \frac{\sin(\Omega t + \phi)}{Z_c \cos \phi} \quad (5)$$

$$Vc \geq (1 + \cos \phi)\, V_{in} \quad (6)$$

Fig.1. Resonant circuit with initial conditions

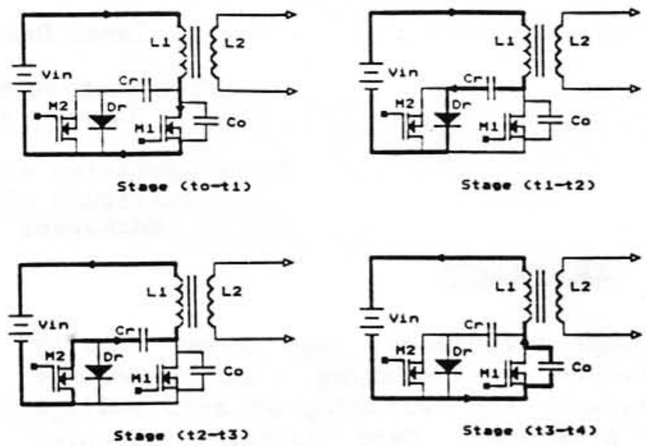


Fig.2. Four stages of operation in ZVS-PWM converter.

current Im, a delay of current in the secondary has to be achieved. In [1] is presented such a technique by using a constant volt-second saturable reactor in the secondary.
However there are several other techniques which can achieve the same delay of the current in secondary.
An effective way to create the initial conditions is by "steering" the magnetizing current back to the input source as is presented in Fig 2.
The operation of this circuit can be divided into the four operating modes depicted in Fig 2.

STAGE 1 (to t1)
At the time to, MOSFET M1 turns on, the current is flowing trough the input source through primary winding L1 and M1. If the power train is forward type, there will be also current flowing towards secondary. In the case of a flyback there will be energy stored in the magnetic field of the transformer.

STAGE 2 (t1 to t2)
At the moment t1 when the primary switch M1 is turned off the magnetizing and leakage current will flow via the reset capacitor Cr and the diode Dr. It is assumed that the resonant frequency of the circuit composed by Cr and L1 is much lower than the switching frequency. As a result the voltage across the Cr

will not have a significant change during operation.

STAGE 3 (t2 to t3)
During the second half of M1 off time the current through Cr and L1 is mirrored back towards the source. This time via M2 which was turned on sometime in between t1 and t2. When M2 is turned on, the diode Dr was forward biased and as result M2 turns on under zero voltage conditions.

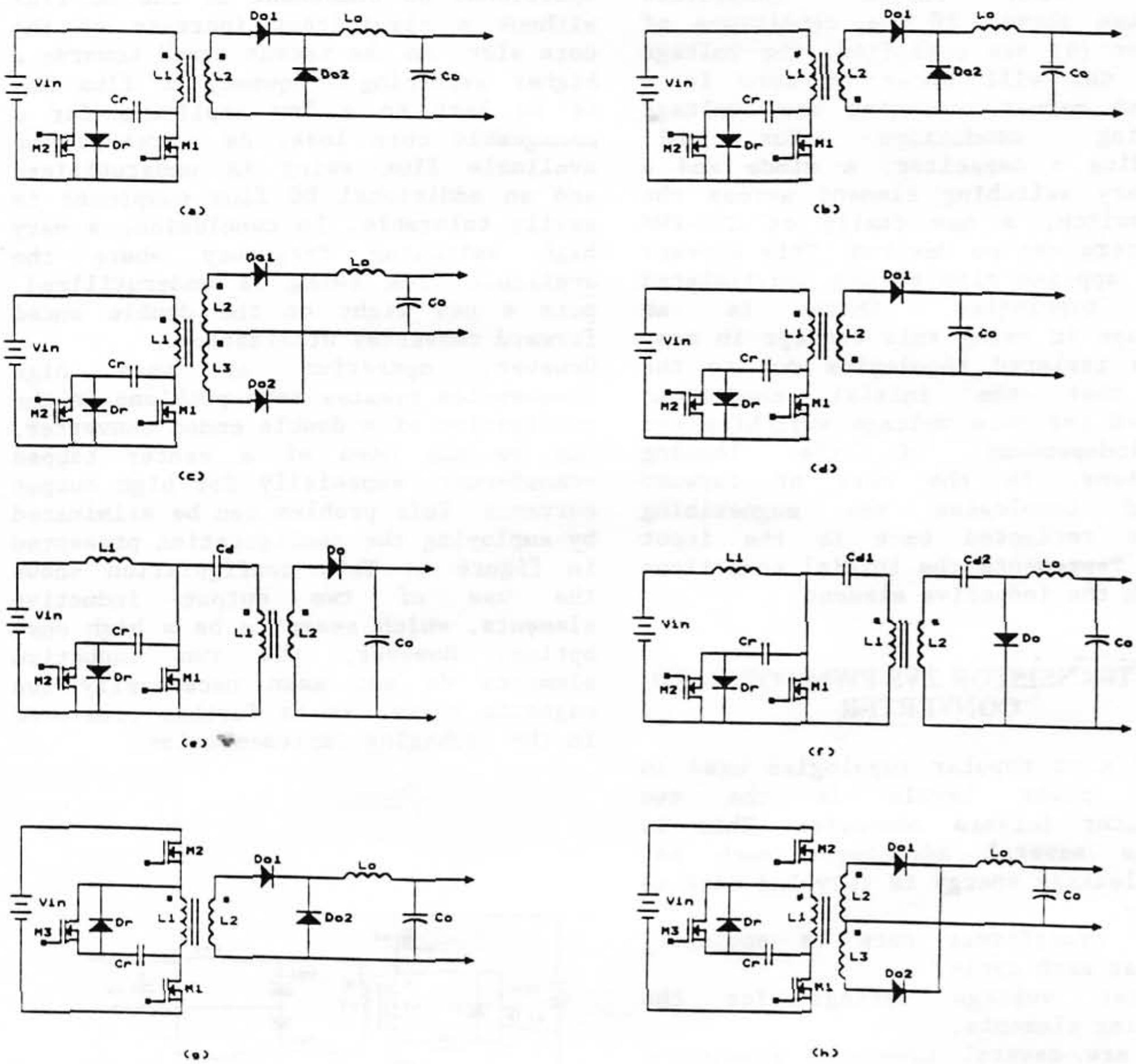


Fig.3. Several ZVS-PWM topologies obtained by utilizing primary current "steering" technique.

(a) Single ended Forward
(b) "Modified" Flyback
(c) Double ended Forward
(d) Flyback
(e) Sepic converter
(f) Cuk converter
(g) Two transistors forward
(h) Two transistors double ended forward

STAGE 4 (t3 to t4)
At time t3 the secondary switch M2, is turned off. The magnetizing current will continue to flow towards the source via the output capacitor of M1. At this moment we have obtained the resonant circuit with initial conditions presented above. If the conditions of equation (6) are satisfied, the voltage across Co, will decay to zero in a resonant manner, creating zero voltage switching conditions for M1. By adding a capacitor, a diode and a secondary switching element across the main switch, a new family of ZVS-PWM converters can be derived. This concept can be applied also to any non-isolated basic topologies. There is an advantage in using this concept in most of the isolated topologies due to the fact that the initial conditions required for zero voltage switching can be independent of the loading conditions. In the case of forward derived topologies the magnetizing current reflected back to the input source represents the initial conditions through the inductive element.

TWO TRANSISTOR ZVS-PWM FORWARD CONVERTER

One of most popular topologies used in medium power levels is the two transistor forward converter. This is due to several advantages such as:
- the leakage energy is recycled back to primary.
- the transformer core is copletely reset at each cycle.
- lower voltage ratings for the switching elements.

There are several drawbacks associated with this topology, one being the duty cycle limitation is only 50 %, thus requiring a larger output filter in comparison to the half and full bridge topology. One technique used to solve this problem is by using a forward double ended configuration. In this topology the magnetizing energy of the transformer is transfered to the secondary during the off time. Unfortunately this adds a DC component to the flux through the transformer.
When the operation frequency is low a relatively high AC flux is tolerable for a given core dissipation. As a result there is not enough margin for adding an additional DC component to the AC flux without a significant increase of the core size. In the recent trend towards a higher switching frequency AC flux has to be kept to a low amplitude for a manageable core loss. As a result the available flux swing is underutilized and an additional DC flux component is easily tolerable. In conclusion, a very high switching frequency where the available flux swing is underutilized, puts a new light on the double ended forward converter utilization.
However, operation at very high frequencies creates some problems in the utilization of a double ended converter, due to the need of a center tapped transformer, especially for high output currents. This problem can be eliminated by employing the configuration presented in figure 4. This configuration shows the use of two output inductive elements, which seems to be a high cost option. However, the two inductive elements do not mean necessarily two magnetic cores, as is further presented in the packaging implementation.

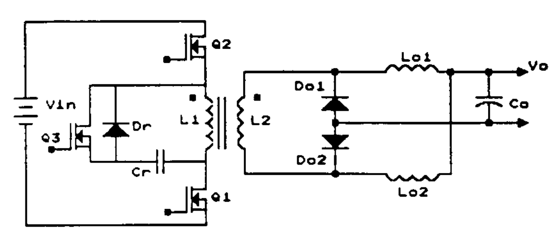


Fig.4. Two transistors ZVS-PWM double ended converter

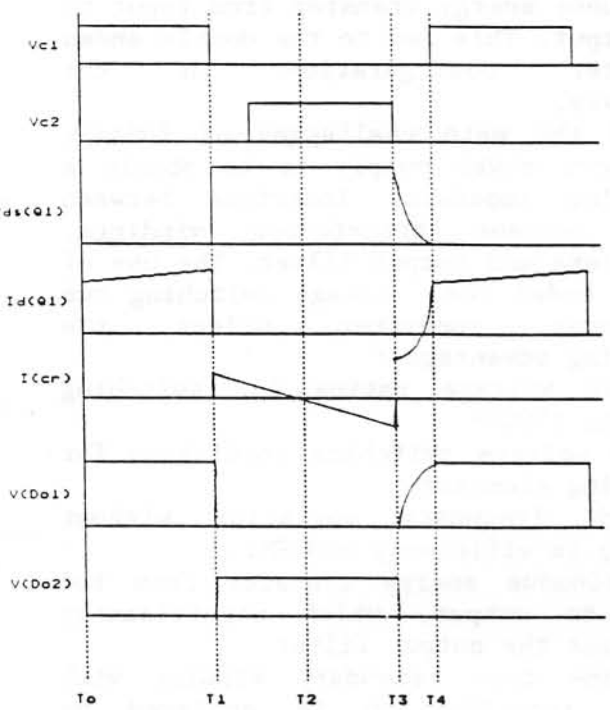


Fig.5. Waveforms of ideal double ended ZVS-PWM converter

The operation of this converter can be divided into the four operating modes shown in Fig 6. In Fig 5 is shown the idealized operating waveforms for the ZVS PWM double ended two transistor forward converter.

STAGE 1 (t0 to t1)
At the time t0, MOSFET Q1 & Q2 turn on, the current is flowing from the input source through primary winding L1 and the output diode Do2, output choke Lo1 and the load. At the same time the current continues to flow through Lo2 via the rectifier Do2. During this period of time there is considerable energy stored in the magnetizing current as would occur in a classic flyback converter.

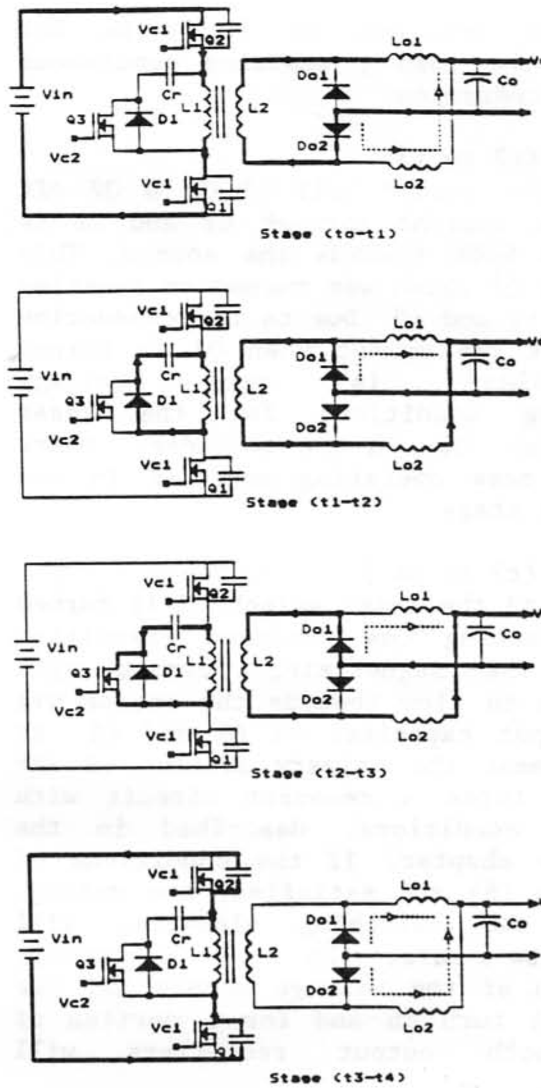


Fig.6. Four stages of operation in two transistor double ended ZVS-PWM Converter

STAGE 2 (t1 to t2)
At the time t1 when the primary switches Q1 and Q2 are turned off, the magnetizing and leakage current will flow through the reset capacitor Cr and the diode Dr. Under the assumption that the resonant frequency of the circuit formed by Cr and L1 is much lower than the switching frequency, the voltage across Cr will not have a significant change. In the secondary , due to the change of the voltage polarity, the current will flow through Do1 and Lo2 towards the load. The current through

Lo1 will continue to flow via Do1 towards the load , assuming continuous mode of operation.

STAGE 3 (t2 to t3)
During the second half of Q1 & Q2 off time the current through Cr and L1 is mirrored back towards the source. This time via Q3 which was turned on sometime between t1 and t2. Due to the conduction of D1 at the moment when Q3 is turned on, there is zero voltage switching conditions for the reset transistor Q3. In the secondary, there is the same operating mode as in the previous stage.

STAGE 4 (t3 to t4)
At time t3 the reset switch Q3 is turned off, starting the resonant transition cycle. The magnetizing current will continue to flow towards the source via the output capacitor of Q1 and Q2. At this moment the primary section of the circuit forms a resonant circuit with initial conditions, described in the previous chapter. If the conditions of equation (6) are satisfied, the voltage across the switching elements, will decay to zero. In the secondary, function of the voltage across L2, the Do2 will turn on and for a portion of time both output rectifiers will conduct.

EXPERIMENTAL EVALUATION

The experimental prototype is a 5V output 100A converter capable of operating from an input voltage range of 200V to 430V. This relatively large input voltage range is due to the necessity of this converter to be compatible to a conventional AC front end or a Power Factor Conditioning stage which boosts the voltage to a 400V bus. The design target was an efficiency greater than 84% and a power density above 30W/inc3. In order to achieve such a large power density the focus is on the minimization of the output choke. The output capacitors usually are demanded by the dynamic load requirements. An effective way to minimize the output choke is through a continuous energy transfer from input to the output. This led to the double ended converter configuration in the secondary.
One of the main challenges of 100Amps and above power supply is to obtain a very low impedance interface between heavy current transformer windings, rectifiers and output filter. The use of double ended zero voltage switching two transistor converter offers the following advantages:
- Lower voltage rating for switching elements (500V).
- Zero voltage switching conditions for switching elements.
- High frequency operation without penalty in efficiency and EMI.
- Continuous energy transfer from the input to output, which significantly minimizes the output filter.
- A one turn secondary winding with double rectification is achieved by using the secondary configuration presented in figures 4 and 6.
- Utilization of the energy contained in parasitic elements.
- Capable of primary duty cycle operation above 50%.
- Zero output ripple for 50% primary duty cycle.
- Low dI/dt and dV/dt in primary and secondary section of the power train.
- A very simple and low cost hardware for the power train.

The power train packaging implementation is presented in figure 7. By analyzing the configuration presented in figure 4, there seems to be a need for two inductive elements. As is presented in figure 7, the need for two independent inductors is solved by using a single low profile E-I core , which is gapped in the outer legs. There is no DC flux component in the center leg and also the AC component is zero at 50% duty cycle. The construction of the main transformer is also simplified due to the use of a single turn secondary winding, which is constructed of 10 mil copper foil connected directly to the cathodes of Do1 and Do2.

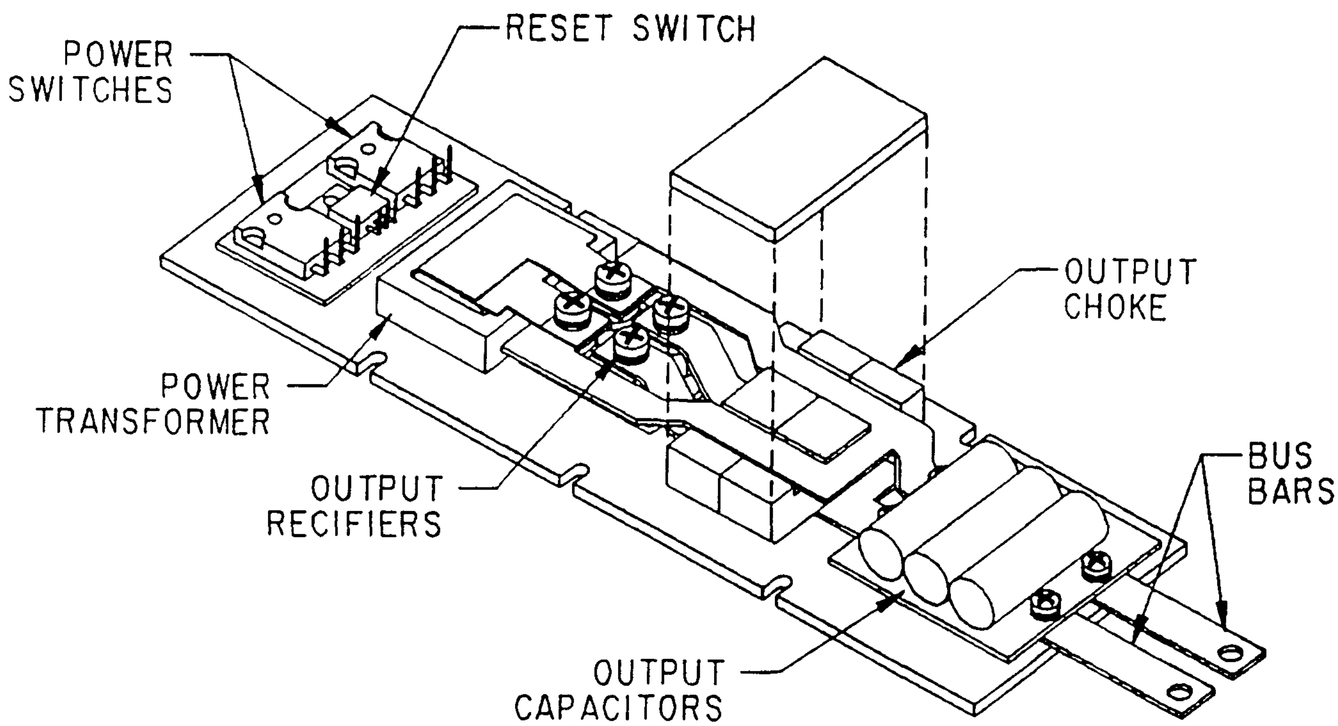


Fig.7. Packaging implementation of the double ended ZVS-PWM converter

The core utilized for the main transformer is PC40EI30-Z, and the flux density for 400V input is presented in figure 8. There is a DC flux component in addition to the AC component, due to the double ended configuration. The turn ratio of the power transformer is 18 to 1 and the leakage reported to primary is 1.5uH. Due to the utilization of the energy contained in the leakage inductance, a relatively large leakage can be tolerated. The leakage inductance delays the current in the secondary and as a result helps in achieving zero voltage switching conditions. However a large leakage inductance decreases the effective duty cycle and affects the efficiency due to the circulating energy between primary and secondary. The secondary topological configuration presented in figure 4 and 6, requires common anode for the output rectifiers. This made the PBYR16035TV from PHILIPS in ISOTOP package the perfect choice. The heatsink which is electrically isolated is screwed directly in the base plate.

The anodes are connected together to one of the output bus bars. The second output bus bar is the merging of the bus bars which go through the output choke.The output capacitor element is implemented by using three electrolytic capacitors connected on the pc board.
For the primary switching elements IRFP450's are used and for the reset switch an IRF840 is used. The experimental current and the voltage waveforms across the main switching elements, are presented in figures 9 and 10, for 200V and 370V input voltages.
The efficiency for Vin=350V at full load is 86%. Most of the losses occured in the output rectifier (60W) and in the main switching elements as conduction losses (13W). Low voltage drop dies such as those used in 62CN030 from International Rectifiers are not availabe yet in the ISOTOP package such as the one depicted in figure 7. By using low voltage drop dies with Vfm of .40V the projected efficiency is 88%.
The size of the prototype is 2x8x.9 in. and the power capability is 600W (5V at

120A)and the power density achieved at the prototype level, with conventional transformer and output capacitors and no surface mounted components, is 42.W/in3.

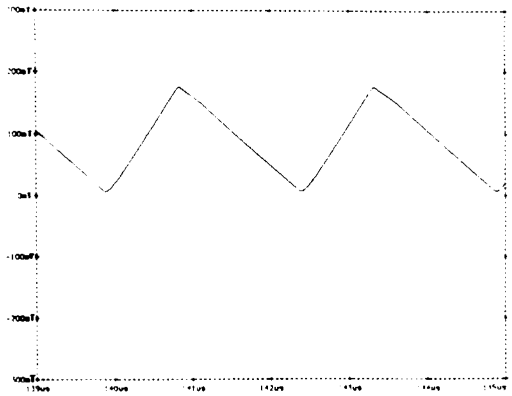


Fig.8. Simulated transformer's flux
Vin=400V Io=100A

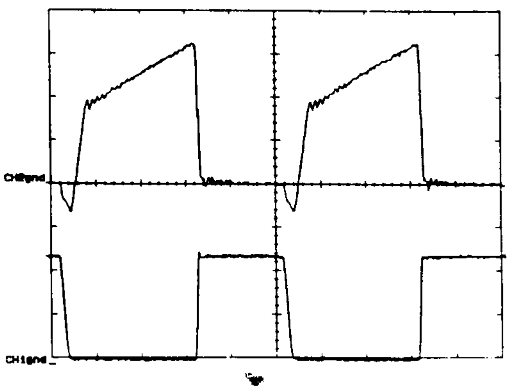


Fig.9. Experimental waveforms Vin=200V
Io=90A Upper trace Id(Q1) 2A/div
500nS/div Lower trace Vds(Q1) 100V/div

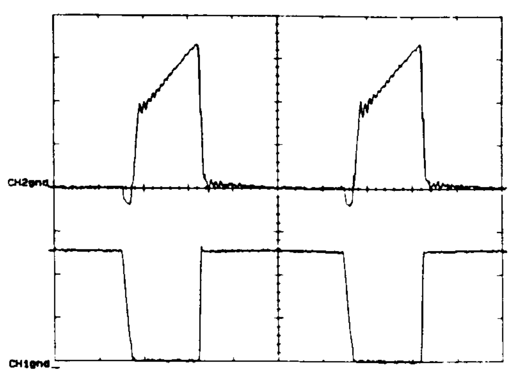


Fig.10. Experimental Waveforms Vin=370V
Io=90A Upper trace Id(Q1) 2A/div
500nS/div Lower trace Vds(Q1) 100A/div

CONCLUSION

By utilizing a supplementary control switch in series with a capacitor, which "steers" the primary current back to the input source in order to achieve zero voltage switching, a new family of ZVS-PWM converters are derived. A member of this family, the double ended zero voltage switched two transistor converter is analyzed. By employing a unique configuration in secondary, which allows double rectification without use of center tap, a very high performance converter in respect of efficiency and power density has been proposed. This topology led to a very simple and cost effective packaging approach of a 100A, 5V output converter with a large input voltage range, 200V to 430V.
This topology combines the advantages of zero voltage switching with the continuous energy transfer to the secondary and a simple and low cost packaging implementation.

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