Zero-voltage and Zero-current-switching of Half-bridge PWM Converter for High Power Applications

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Abstract. The design and control of a half-bridge converter that ensures zero voltage and zero current shifting of electronic switches throughout the load band for a large range of input voltage is described in this paper. The new proposed topology of the converter achieves a substantial reduction of losses due to the shifting of electronic switches and oscillating currents. The proposed topology has a simple technical scheme with minimal number of control elements with a total low price, as well. The control of the proposed converter can be implemented by applying the technique of pulse width modulation (PWM). The functionality, stability and performance of the proposed converter topology have been verified on an experimental converter at power range 420 W (400V, 50V).

Keywords**:** half bridge (HB) converter, pulse width modulation (PWM), zero voltage switching (ZVS) zero current switching (ZCS).

Convertor pentru utilizarea în instalaţii energetice de tip semi-punte cu modulaţia duratei impulsului şi comutaţia la tensiune şi curent zero

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Rezumat. În lucrare se descriu elemente privind procedeul de proiectare şi particularităţile de funcţionare a unui convertor de tip semi-punte. În acest convertor comutarea cheilor electronice se produce la valorile zero a tensiunii şi curentului pentru orice bandă de valori a tensiunii de alimentare şi a sarcinii convertorului. Topologia nouă propusă a convertorului asigură o reducere semnificativă a nivelului pierderilor de energie în procesul de conversie ca urmare a distribuirii optimală a impulsurilor şi curenţilor cu formă oscilatorie. Topologia propusă a convertorului se caracterizează de o schemă electrică echivalentă simplă, ce include un număr minimal de componente electronice active şi pasive. Aceasta asigură şi un preţ mai redus a convertorului. Dirijarea cu funcţionarea convertorului se bazează pe aplicarea conceptului de modulaţie a duratei impulsurilor (PWM). Funcţionalitatea, stabilitatea şi performanţa topologiei convertorului propus au fost verificate prin testarea mostrei convertorului experimental cu puterea de 420 W (400V, 50V).

Cuvinte-cheie**:** convertor în schema semi-punte, modulaţia duratei impulsului v(PWM), comutaţia la tensiunea zero (ZVS), comutaţia la curentul zero (ZCS).

Преобразователь для энергетических установок полумостового типа с ШИМ и коммутации при нулевых значениях напряжения и тока

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Аннотация. В работе рассмотрены вопросы проектирования и управления полумостовым преобразователем в режиме коммутации силовых электронных ключей при нулевых значениях напряжения и тока. Такой режим характерен для широкого диапазона изменения входного питающего напряжения и изменения нагрузки преобразователя. Предложенная новая топология преобразователя обеспечивает существенное снижение потерь сак следствие переключения ключей при прохождении напряжения и тока через нуль. Кроме того, предложенная топология имеет простую электрическую схему замещения и содержит минимальное числом электронных активных и пассивных элементов, что обеспечивает и снижение стоимости преобразователя. Управление преобразователя: на основе широтно-импульсной модуляции (ШИМ). Функциональность, стабильность и технические показатели предлагаемого топологии реализации преобразователя были проверены на экспериментальной модели устройства мощностью 420 Вт (400В, 50В).

Ключевые слова: полумостовой преобразователь, широтно-импульсная модуляция (ШИМ), коммутация при нулевом напряжении (ZVS), коммутация при прохождении тока через нуль (ZCS).

I. INTRODUCTION

The most currently used DC/DC converters are derived from three basic topologies of one quadrant: Buck, Boost and Buck-Boost.

At high power, the currently preferred topologies for DC/DC converter with the insulating transformer are half bridge and full bridge. The main advantages of these topologies include the constant functioning frequency (that allows the optimal design of the magnetic transformer and of the filtering elements), the PWM control (that ensures minimal VA tension) and the wide range of control and maneuverability. However, the increasing of switching losses under the increasing frequency and the presence of high voltage tension induced by parasitic inductances are the major disadvantages of these topologies. To improve the performance of hard switching converters various soft switching schemes (ZVS and ZCS) have been proposed.

A pseudo-resonant DC/DC converter proposed by Patterson [l] demonstrates the possibility of creating a conventional PWM control with resonant switching. However, the reverse recovery of output diodes results in high voltage peaks and therefore requires a snubber circuit. Although the use of snubber in [2] and [3] offers practical and effective solutions to the secondary–call problem, but do not offer any improvement of the switching losses.

Another topology made with PWM control and with resonant switching is the full bridge ZVS (FB-ZVS) PWM converter [4]. In this topology, the leakage and the magnetizing inductances of the transformer in addition to the value of the capacity of the electronic switches are used efficiently to achieve ZVS and ZCS. The disadvantage of this system lies in the fact that it uses a large number of passive semiconductor elements, that leads to the increased cost of the installation and to increasing of the energy losses in the system. Furthermore, the frequency converter includes a transformer with three windings, which leads to the increase in its weight, and therefore its cost and energy losses are increasing. In addition, the system uses a large number of ferromagnetic elements.

We propose some improved topology of the DC/DC converter. It is based mainly on a half bridge topology (HB). The shifting of ZVS and ZCS electronic switches here is realized by using the energy stored in the magnetized inductance of the frequency transformer by isolation between the medium and low voltages and by the leakage inductance of the transformer.

The proposed topology ensures the reduction of the manufacturing cost of the system by excluding of some functional elements. Also, in the proposed converter only one high-frequency transformer is used with a simplified constructive design with two windings. The use of the transformer with two windings ensures lower power consumption of active materials in comparison with the frequency transformers in the most known topologies. In this case the weight of the conductive material, that ensures the robustness of the proposed converter, decreases. This fact contributes to the lowering of the cost of production of the converter. Reducing the cost of production is also achieved by the reduction of the number of connections between the functional elements. Also in this topology the efficiency of the DC/DC converter is increased by decreasing of the number of passive semi-conductor elements and by decreasing of the number of inductive elements: the proposed functional scheme includes only one coil for intermediate storage of energy in the work cycle. The exclusion of these elements, and therefore the exclusion of the losses caused by the currents in them, contribute to increasing the efficiency of the converter.

This paper presents a comprehensive analysis of the proposed topology: the functionality and stability, the working principle and the evaluation of different circuit losses. It also contains the simulation results (PROTEUS software) and experimental testing of the converter sample with power of 420W.

II. OPERATION AND ANALYSIS

The basic structure of the proposed converter (fig. 1) is described in [5].

The scheme includes a DC power source Vs, two frequency capacitors C1 and C2 connected in series, two electronic switches S1 and S2 connected in series. The primary winding Np of the high-frequency transformer TF is connected between the connection nodes of the frequency capacitors C1 and C2 and of the electronic switches S1 and S2. The ferromagnetic core of the transformer is made with a minimum interferon. The switching capacitor CS through diode DS2 is connected in parallel with the primary winding Np. Then the coil L for storing energy in the work cycle and the filter capacitor CF are connected to the output of the secondary winding Ns by a semi-conductive element Sd. In addition the load RL is connected in parallel with the filter capacitor CF.

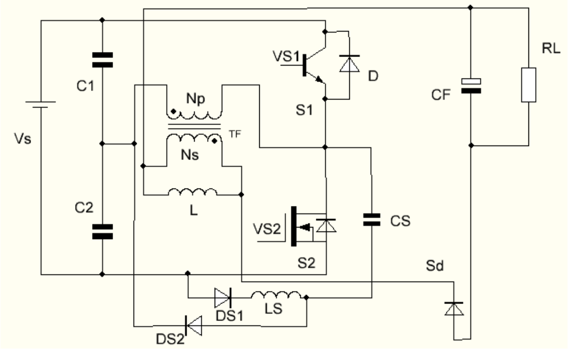

Fig.1. Proposed HB ZVS and ZCS converter

The control of the electronic switches S1 and S2 is based on the technique of changing the control pulse width PWM. To illustrate the principle of operation at the equilibrium state, we set the following assumptions:

1) All components are ideal.

2) The inductance of the output filter L is large enough to be treated as a constant current source during a switching period.

The proposed converter has five operating modes. The equivalent circuits of operating modes and the key waveforms are shown in Fig. 2 and Fig. 3, respectively.

The DC/DC converter works as follows:

When applying direct current voltage Vs and in the presence of the control impulses VS1, VS2 and VSD (see Figure 1) for keys S1, S2 and Sd, two operating modes of the converter can be provided. The first mode is ensured by adjusting the duration of the control pulse VS2 to the electronic key S2. The energy from the direct current source Vs at this mode is accumulated in the magnetic field of the frequency transformer TF and in the coil L for storing the energy in cycle.

The second mode is ensured by adjusting the duration of the control pulse VS1 to the electronic key S1. At this mode the energy from direct current source Vs is transferred directly into the load RL.

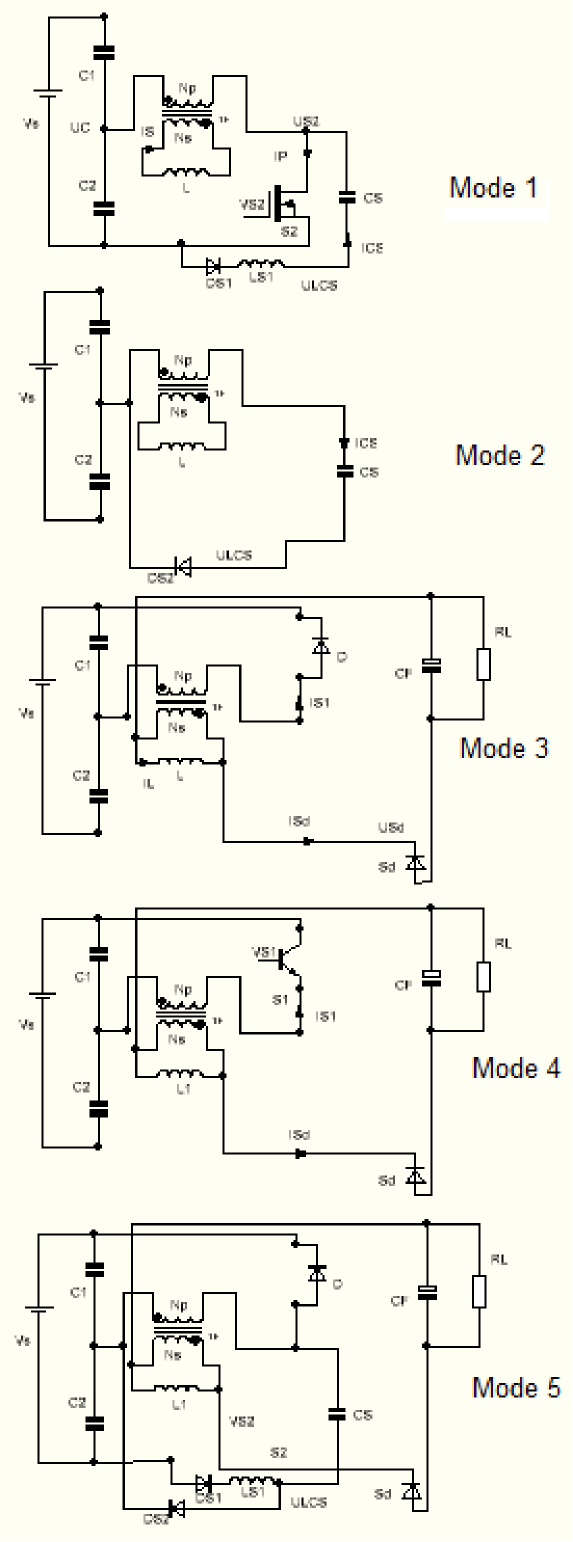

Fig.2. Operation of DC/DC converter in the work cycle

Let analyze now the working principle of the DC/DC.

A. Mode 1

The initial conditions of the working cycle of the proposed converter are:

- At the beginning of the cycle the voltage values of capacitors C1 and C2 (Figure 1) are equal between them and, also, equal to ½ of the power supply voltage Vs.
- The voltage of switching capacitor CS is equal to the power supply voltage Vs.

For given value of time (fig. 2 and 3 t_0) for control impulse VS2 is applied to electronic key S2. When opening the electronic key S2, the frequency capacitor C2 begins to discharge, and the frequency capacitor C1 (see Fig. 1 and Fig. 3, the tension noted by Uc) begins to charge through the primary winding Np of the high frequency transformer TF to form a current Ip. At the same time, the circuit composed of capacitor CS, inductance LS and diode DS1 assures the change of polarity of capacitor CS voltage, that's why in this case we have a rezoning circuit of voltages. The soft switching conditions are following: $f_{sw2} > f_{rez}$, where f_{sw2}- the value of the switching frequency of the electronic key S2; f_{rez}- own resonance frequency of the circuit consisting of capacitor CS, inductance LS and diode DS1.

Because of the mutual electromagnetic relationship between the primary winding Np and the secondary winding Ns of the high frequency transformer, another current Is appears in the circuit consisting from the secondary winding Ns and the coil L for energy stored in cycle. These currents Ip and Is, begin to increase linearly (see fig.3 for the interval t_0-t_1) and are determined by the inductance of the primary winding Np, i.e., the physical size of air gap between the magnetic core of the transformer TF and the coil inductance L is used to store the energy in cycle. So, due to the leakage of the currents Ip and Is, the energy storage in the magnetic field of the high frequency transformer TF and the coil L is ensured.

B. Mode 2

At the extinction of the control impulse VS2 (see fig. 2b and fig. 3 for t1) applied to the electronic key S2 and the closing of this key S2, the current IS2 drops to zero and the switching capacitor CS ensures the maintenance zero value of the tension on the key S2 (see fig. 2 for the interval t1 - t2). This fact reduces switching losses in the electronic key S2. From this time (see fig. 3 for t2) the switching capacitor CS begins to charge through the diode DS2 (see fig. 2b and fig. 3 for the interval t2 - t3) and the electromotive tensions of the windings Np and Ns of the transformer TF and the coil L change its polarity.

Soft switching conditions are described in [5], which are formulated in the relationship $E_{off} = \frac{1}{12}\frac{I_{S2}^2 t_f^2}{2CS}$, where E_{eff} – is the closing energy of the power transistor S2;

I_{S2} – the value of current through electronic key S2 at the carry out of its closing process;

$t_f = t_4 - t_1$ the time delay between control pulses of transistors (see Fig. 3); CS - the capacity of switching capacitor.

C. Mode 3

When the electromotive tension of the secondary winding Ns of the frequency transformer TF and the coil L for storing energy in cycle will be equal to the voltage load RL, the semiconductor element Sd (see fig. 2c and fig. 3 for t_3) and the inner diode of the electronic key S1 will open, that ensures the appearance of two circuits.

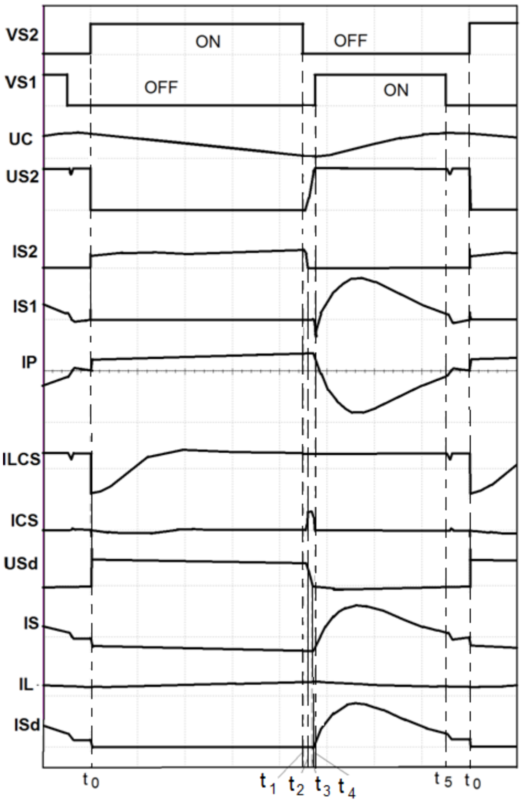

Fig.3. Key waveforms of proposed converter power stage for variable duty cycle PWM control

The first circuit is composed of the frequency capacitors C1 and C2, the primary winding Np, the inner diode of the electronic key S1, through which circuit energy leakage flux of the frequency transformer returns to the capacitors C1 and C2.

The second circuit consists of the semi-conductor element Sd, the primary winding Np of the high frequency transformer TF, the coil L for storing energy in cycle, the load RL, the semi-conductor element Sd. This circuit provides the transfer of stored energy in the high frequency transformer TF and coil L into load RL (see fig. 3 for the interval t_3-t_4).

D. Mode 4

In this time interval to the electronic key S1 the control impulse VS1 is applied. When the current through the electronic key S1 changes its polarity (see fig. 2d and fig. 3 for t_4), the circuit consisting of the following elements is opening: frequency capacitors C1 and C2, the electronic key S1, the primary winding Np of the frequency transformer TF, the frequency capacitors C1 and C2. Because of the mutual electromagnetic relationship between the primary winding Np and the secondary winding Ns there appears another circuit consisting of the secondary winding Np of the frequency transformer TF, the load RL, the semi-conductor element Sd, the secondary winding Ns. From this time (see fig. 2 for t_4), through the described above circuits the energy of capacitors C1 and C2, i.e. from the source, is transferred directly into the load (see fig. 3 for the interval t_4-t_5). Because the values of capacities C1 and C2 are in resonance with the value of the inner inductance of the frequency transformer TF, the current through the electronic key S1 has a bell shape and in the moment of closing (see fig.3. for t_6) decrease to almost zero. Therefore, this key S1 disconnects when the current value is equal to zero (which ensures ZCS).

Soft switching conditions are defined so $f_{sw1} > f_{rez}$, where f_{sw1}- the value of the switching frequency of the electronic key S1; f_{rez}- own resonance frequency of the circuit consisting of capacitors C1, C2 and inductance of frequency transformer TF.

E. Mode 5

When closing the control impulse VS1 (see fig. 2e and fig. 3 for t_5) is applied to the electronic key S1, this key S1 is closing without stress because the current IS1 through this key has the value almost equal to zero. This leads to the reduction of losses when switching the electronic key S1. At the moment of time t_0 it is applied a new control impulse VS2 to the electronic key S2 and the operating process of the converter repeats in a new work cycle.

In the proposed converter to achieve soft switching mechanism for S2 electronic key is used only switching inductance LS and switching capacitor CS having low values and the switch of electronic key S1 is ensured by the regime of resonant circuit including the capacitors C1 and C2, leakage inductance of high frequency transformer TF.

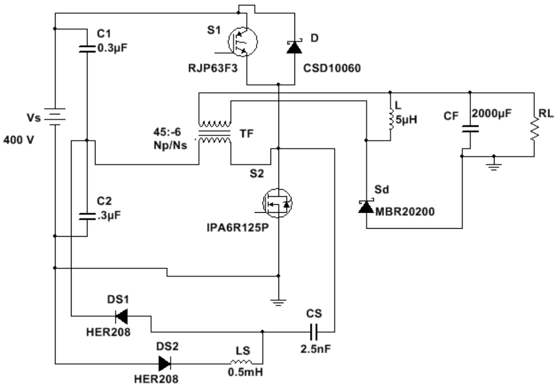

Fig.4. Experimental 0.42 kW HB ZVS and ZCS converter power-stage components

The measuring of the efficiency of the proposed converter was performed with various semi-conductor elements Sd. In the first case, we used a Schottky diode MBR20200 and in the second case a MOSFET transistor of type IRFB4115.

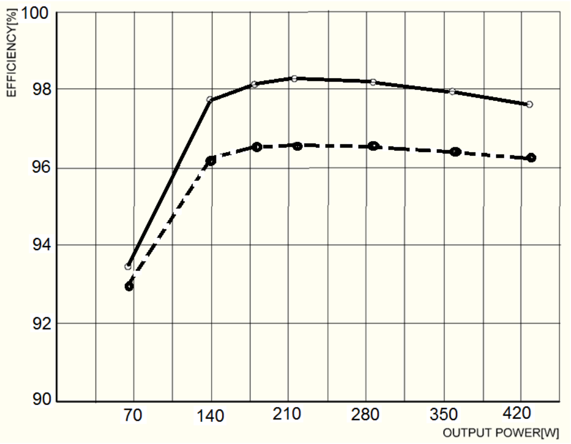

Fig. 5. Efficiency of proposed converter as functions of output power (dashed line using a Schottky diode and solid line using the MOSFET transistor)

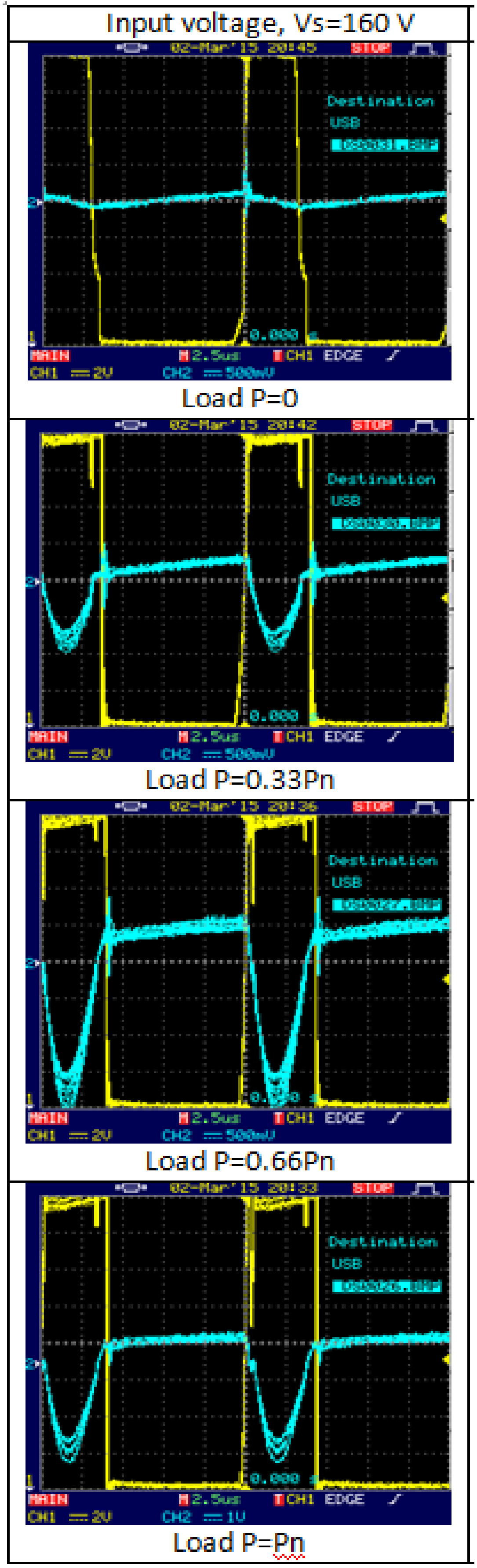

Fig.6a. Diagrams of voltage Us2 and current Ip for input voltage Us=160 V for different loads P

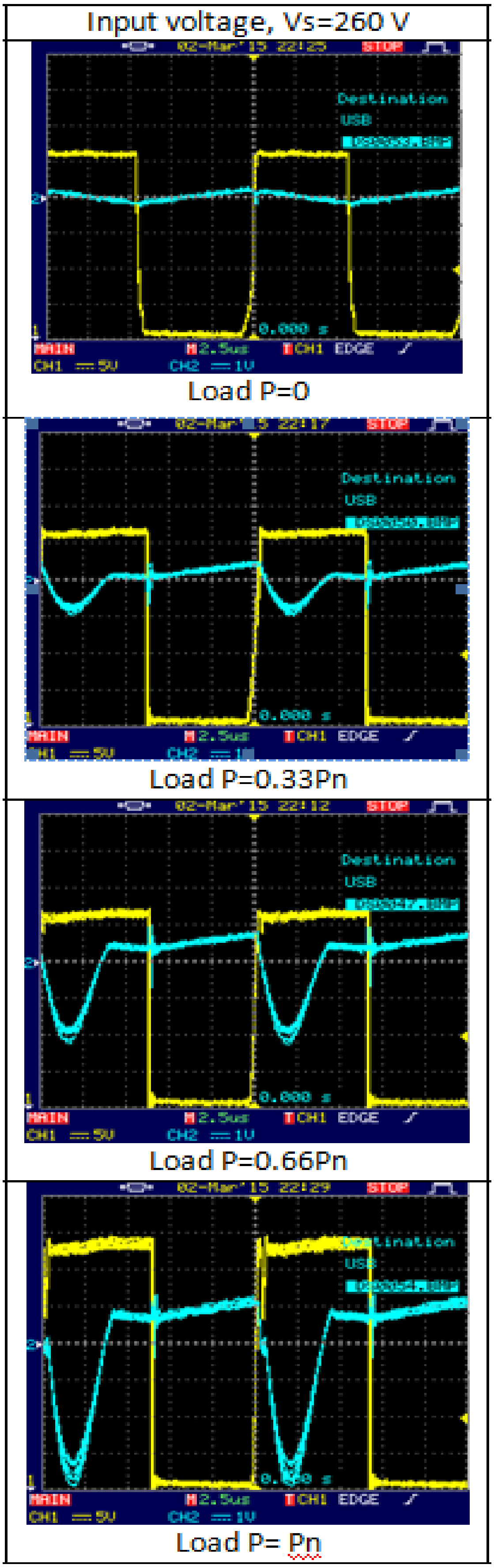

Fig.6b. Diagrams of voltage Us2 and current Ip for input voltage Us=260 V for different loads P

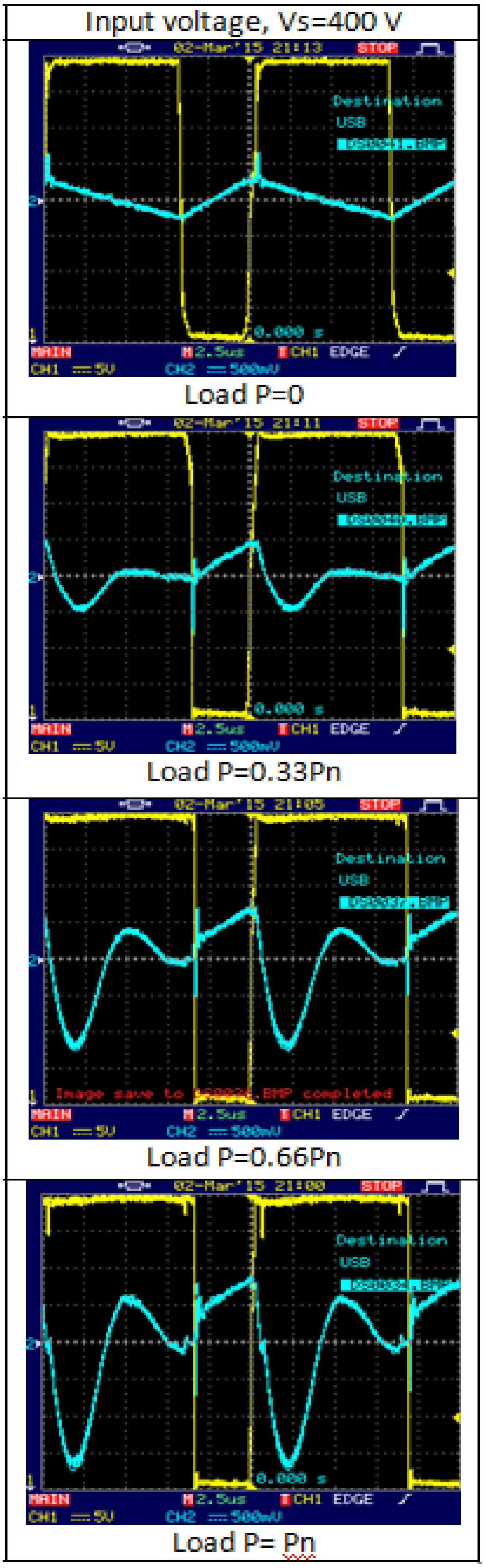

Fig.6c. Diagrams of voltage Us2 and current Ip for input voltage Us=400 V for different loads P

Then the tests were performed up to the maximum power that is a breadth of 50% of the impulse VS2 from the period. The proposed topology enables an impulse breadth greater than 50% from the period which is beneficial in reducing the input voltage Vs.

It has been estimated the energy efficiency indicator of the convertor on the results of experimental tests. As a calculation results from experimental testing has been obtained a value of convertor power density for more than 80 W/inc^3. The experimental tests were carried out without forced air cooling.

For sample converter executed experimentally voltage Us2 and current Ip of primary coil of transformer of high frequency switching mode key S1 and S2 were measured (see Fig. 6). Diagrams of fig. 6 are obtained for different values of input voltage Vs = 160, 260, and 400 V as well as different values of the load converter P=0.33Pn, 0.66Pn 1.0Pn in the stabilization regime of the output voltage level 35 V.

III. CONCLUSIONS

We have presented above a new converter with soft start of half-bridge HB type, which offers ZVS and ZCS on a wide range of input voltage and output load. It contains a small number of power elements and a simple control scheme that allows its use in high voltage and high power converters.

Operation and performance of the proposed topology was checked experimentally on a converter with 0.420 kW power, at output voltage of 50 V, on a constant work frequency 80 kHz and DC input voltage 400V. The maximum reached efficiency is of 98.3%.

The density of power has been calculated and for above described convertor it is equal to 80 W/inc3.

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