

USING PLANAR TRANSFORMERS IN SOFT SWITCHING DC/DC POWER CONVERTERS

POUŽITIE PLANÁRNYCH TRANSFORMÁTOROV V MÄTKO SPÍANÝCH VYSOKOFREKVENČNÝCH MENIČOCH

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Summary In recent years, the demand for wide applications of highly regulated, reliable power supplies, and the desire to have smaller size, lighter weight and higher efficiency of power electronics systems has been increased. The tallest and heaviest components on printed-circuit-boards are often magnetic components. The answer for miniaturization and material performance can be planar magnetic technology. This paper focuses on the power planar magnetic circuits, with respect to application possibilities of these alternative and attractive magnetic components in modern, soft switching, low profile power supplies.

Abstrakt V posledných rokoch narástla potreba po vysoko regulovateľných a spoľahlivých zdrojoch, s malými rozmermi, váhou a vysokou účinnosťou. Medzi najväčšie a najťažšie konštrukčné prvky, montované na plošné spoje, patria magnetické komponenty. K ich miniaturizácii a pre lepšiemu využitiu magnetického materiálu, môže v značnej miere prispieť planárna magnetická technológia. Tento článok je zameraný na planárne magnetické obvody, z hľadiska použiteľnosti týchto atraktívnych a perspektívnych prvkov, v moderných mätko spínaných zdrojoch s malými rozmermi.

1. INTRODUCTION

Planar transformers first became known at the beginning of the 80s. Their worldwide acceptance has only recently begun, due to technological advances that have enabled drastic cost reductions, making them a viable and competitive product. By employing planar technology, bulky, wire wound transformers have been superseded in many applications by coils encapsulated within multi-layer printed-circuit-boards (PCBs) and sandwiched between state-of-the-art low-profile ferrite cores to make small, flat components ideally suited to PCB mounting. The major benefits of such transformers and inductors, is a size and weight reduction of up to 60 %. This technique is now employed to produce low profile, highly efficient, transformers as large as 20kW [1].

The primary appeal of planar magnetics is obvious: in many applications there is a great benefit to having power transformers and inductors that are not tall. Printed circuit boards are only as compact as the tallest component on them, and that is often a magnetics. But low height is not the only reason for the growing use of planar ferrites in power magnetics. Planar designs offer advantages that include low leakage inductance, excellent repeatability of performance, economical assembly, mechanical integrity, and superior thermal

characteristics. With the arrival of industry standard core size and geometries, offered by multiple ferrite vendors in power ferrite materials, planar magnetics are being used in a growing proportion of new power supply designs.

2. CURRENT TRENDS IN DEVELOPMENT OF POWER SUPPLIES

For many years, high efficiency power processing circuits has been achieved by operating power semiconductor devices in the switching mode, whereby switching devices are operated in either the ON or OFF states as in the Pulse Width Modulation (PWM) method. In PWM converters, switching of semiconductor devices normally occurs at high current levels. Therefore, when switching at high frequencies these converters are associated with high power dissipation in their switching devices. Furthermore, the PWM converters suffer from EMI caused by high frequency harmonic components associated with their quasi-square switching current and/or voltage waveforms, with today's power semiconductor and circuit technology PWM converters can operate up to 100 kHz. Unfortunately, even though the technological advancement of PWM switch mode converters has resulted in faster switching devices, their operating frequency is limited by the reasons mentioned above.

Nowadays, in both techniques Zero-Current-Switching (ZCS) or Zero-Voltage-switching (ZVS), the switching losses in the semiconductor devices are avoided due to the fact that current through or voltage across the switching device at switching point is equal to or near zero. This reduction in the switching loss allows the designer to attain a higher operating frequency without sacrificing converter efficiency. By doing so, the resonant converters show promise of achieving what by the PWM converters could not be achieved, is the design of small size and weight converters. Currently, resonant power converters operating in the range of a few megahertz are available. Another advantage of resonant converters over PWM converters is the decrease of harmonic content in the converter voltage and current waveforms. Therefore, when the resonant and PWM converters are operated at the same power level and frequency, it is expected that the resonant converter will have lower harmonic emission.

There are many soft switching techniques available in the literature to improve the switching behaviour of dc-to-dc resonant converters. At the time of writing these words, intensive research in soft switching is under way to further improve efficiency with increased switching frequency of power electronic circuits. From a circuit standpoint, a dc-to-dc resonant converter by three major circuit blocks can be described. The dc-to-ac input inversion circuit, the resonant energy buffer tank circuit, and the ac-to-dc output rectifying circuit. Typically, the dc-to-ac inversion is achieved by using a various types of switching network topologies. The resonant tank, which serves as an energy buffer between the input and output, is normally synthesized by using loss-less frequency selective network. The purpose of that network is to regulate the energy flow from the source to the load. Finally, the ac-to-dc conversion is achieved by incorporating rectifier circuits at the output section of the converter.

3. INCREASED SWITCHING FREQUENCY AND SOFT SWITCHING

A new class of dc-to-dc converters have been thoroughly investigated in recent years, known in the literature as soft-switching resonant converters. Generally speaking, soft switching means the one or more power switches in a dc-dc converter have either turn ON or turn OFF switching losses eliminated. This is on contrast to hard switching when both turn-ON and turn-OFF of the power switches are employed at high current and high voltage levels. Two major techniques are generally employed to achieve soft switching: *Zero-Current-Switching* and *Zero-Voltage-switching*.

One approach is to create a full resonance phenomenon within the converter through series or parallel combinations of resonant components. Resultant converters are known generally as resonant converters.

Another approach is to use conventional converters, buck, boost, buck-boost, Ćuk, SPEC, and then replace the switches by resonant switches that accomplish the same loss elimination mentioned above. Because of the nature of the PWM circuit, resonance occurs for shorter time interval than the full resonance case. As a result, this class of converters combines resonance and PWM, which are appropriately known as quasi-resonant converters. Conventional PWM switching converters still have several limitations among them: High Electromagnetic Interference (EMI), and because of high stress levels on power semiconductor devices, their switching speeds are limited to under 100 kHz.

As switch mode dc-to-dc converter, resonant converters are used to convert dc-to-dc through an additional conversion stage: the resonant stage in which dc signal is converted to high frequency ac signal. The potential advantage of resonant converter include the natural commutation of power switches, resulting in low switching power dissipation and reduced component stresses, which in terns results in increased power efficiency and increased switching frequency; higher operating frequencies results in reduced size and weight of equipment and results in faster responses; possible reduction in EMI problems.

Since the size and weight of the magnetic components (inductors and transformers) and capacitors in a converter are inversely proportional to the converter switching frequency, many power converters have been designed at *progressively higher frequencies* in order to reduce excessive size and weight and obtain fast converter transients. In recent years, the market demand for wide applications, highly regulated power supplies, and the desire to have *smaller size* and *lighter weight* power electronics systems have been increased. The creation of any modern high-efficiency, resonant power converter requires a proper selection of inductive components, like the transformer and inductor. The answer for miniaturization and material performance can be using *progressively higher frequency* and *planar magnetic technology* in soft switching, power converter topologies.

4. PLANAR TRANSFORMERS

The primary differences between traditional magnetic components and Planar Magnetics are found in the core geometry and the winding structure. *Planar Magnetics (PM)* feature a core with a larger cross section and windings that have a fewer number of turns - compared to traditional magnetic components. PM windings are built from pre-tooled parts - copper foils built on PC boards or self-supported lead frames. In contrast, classical magnetics employ solid or LITZE wires. As a result, PM enjoy several benefits over their classical cousins, including up to *3 times* the power density, up to *200A* per winding layer, *5W-20kW* single unit power capacity, and a *97 – 99 %* efficiency [9]

without volume increase - all at a weight that's almost *half* that of classical magnetics.

In whatever design approach is chosen, the creation of a high-efficiency power supply design requires proper selection of many components and materials, such as filter capacitors, regulator circuits, control circuits, power transistors, and, of course, *the transformer*. Compared to a conventional power supply with traditional magnetic components, a soft switch – mode power supply with planar magnetics features higher efficiency, increased reliability, smaller size and lighter weight.

In most resonant switching methods, the switching frequency is usually adjusted to match internal circuit resonant in the power supply. Adjustments are made to approximate open-circuit or zero-current-switching and closed circuit or zero-voltage-switching conditions. Both approaches yield low switching losses, allowing power supply to operate at high switching frequencies. Planar transformers can be designed for use with all modern switch-mode power-supply topologies. Their unique, magnet-wire-free structure ensures consistent performance and high reliability over long operating lifetimes.

Planar magnetic transformer technology uses of flat copper lead frames and flat copper spirals to eliminate magnet wire wound around large ferrite cores. In a conventional magnetic transformer, copper wire is wound around a low-loss ferrite core. Rather than use wound copper wire, a planar transformer is assembled with precision copper lead frames or one or more flat copper spirals etched on thin sheets of dielectric material (Fig. 1). The spirals or lead frames are stacked on flat, high frequency ferrite cores to form the transformer's magnetic circuit. The core material is bonded with a low-grain-diameter epoxy to minimize core losses. High-temperature (+130°C rating) insulators within the stack of spirals or lead frames ensure high isolation between windings [1].

This type of transformer offers *various benefits*, including:

- High power densities
- High efficiency at high operating frequencies
- Good high-voltage isolation
- Low parasitic reactance
- Light weight
- Superior Repeatability
- Especially High Reliability
- Low Profile
- Superior heat dissipation

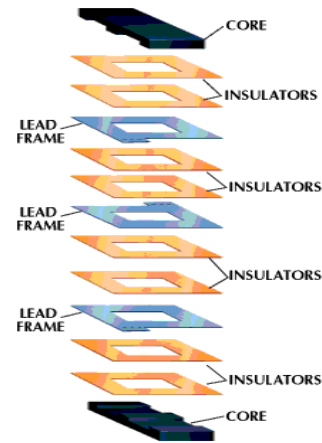


Fig. 1. Planar magnetic transformer

The most frequently discussed planar ferrites are the E cores, but the E shape is not the only planar geometry. Other conventional shapes are produced in low profile versions. These include PQ, RM, and pot cores, (Fig. 2). There are several advantages to these styles. One is the center-posts and skirt IDs are round, resulting in a more efficient use of copper. Another advantage can be the efficient use of board real estate, especially with the RM geometry, which can be designed for square footprint.

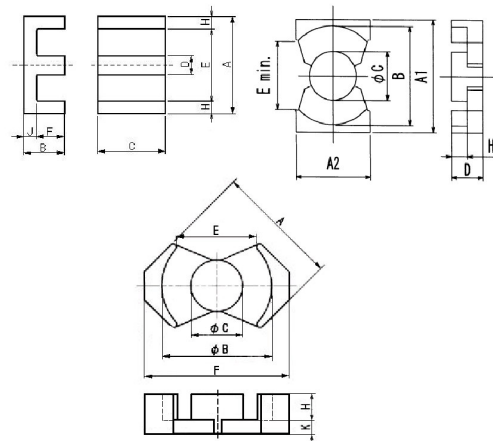


Fig. 2. The planar E, PQ and RM core geometries [10]

Planar designers have an incentive to push flux density higher than they would in similar, traditional designs. Any magnetics design involves a trade-off between copper losses and core losses. In other words, using more turns of copper results in lower flux density and lower core loss; but using fewer turns of copper allows a lower current density and lower copper loss. In the typical planar device, the minimum total losses are achieved by favouring the current density, and letting the flux density run higher than traditional designs might allow.

Planar geometries by their nature have smaller windows relative to the total device volume, so space for windings is at a premium. With printed circuit windings the largest practical percentage of window actually filled by copper is typically lower than with magnet wire. For these reasons, there is much to be gained by keeping the turns count to a minimum.

At the same time, planar geometries have a higher ratio of surface area to volume. They are literally spread out over a greater area, which is a favourable thermal situation. On average, the core and conductor material that is generating heat is closer to the surface; and there is much greater surface per unit of volume to radiate heat. Finally, there is a natural opportunity to attach heat sinks or blow air against the large flat ferrite surfaces.

Another potential advantage of the planar magnetic is mechanical integrity. In applications that will be exposed to vibration or shock, the tall, heavy mass of a traditional ferrite magnetic is vulnerable to becoming dislodged due to high angular forces. In contrast, the planar magnetic has a center of mass located close to - or even within - the board it is attached to. There is a trade-off, however. Planar cores themselves are more susceptible to breaking under mechanical or thermal stress. Traditional cores are more compact; planar cores present thinner cross sections for the same mass.

In cores operating at typical modern switching frequencies, the flux density is loss limited, rather than saturation limited. The planar designer is able to push the flux density higher, for the reasons described above, but she or he must still pick a core loss limit that results in acceptable overall efficiency and temperature rise. One fact that may not be obvious is that for a given voltage, core and winding, an increase in frequency results in a decrease in core loss. This is significant when thinking about planar magnetics, because there is not much winding flexibility.

Four basic options (Fig. 3.) are available for winding the planar transformer or inductor [1], [2]:

- Stacked printed circuit boards
- Stand – alone multi – layer board
- Integrated through – board
- Wire

When using printed *circuit windings*, there are several benefits. Because the winding layout is fixed, and cannot vary in the way that conventional windings do, the repeatability of performance from one unit to the next is very good. Leakage inductance and proximity effects are quite low. By interleaving windings (P-S-P), typical leakages are less than 1% of primary inductance, down to 0,1%. There are

drawbacks to interleaving, namely capacitance and assembly complexity. Each of these can be planned for, since they are consistent. The capacitance may even be exploited in some resonant designs.

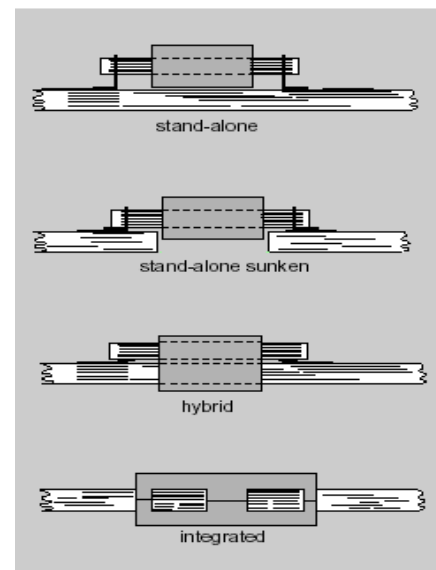


Fig. 3. Several types of planar devices

It would be problematic to implement coils with hundreds of turns using printed circuit windings. Fortunately, because the typical application is power, the turn counts are generally low. Depending on the topology of the circuit being used, there may be a need for the added complexity of sense windings or reset windings. The more practical problem that is encountered is making sure that the true copper cross sections are large enough to conduct full load currents.

Because conventional transformers generally rely on cylindrical wire windings around a ferrite core, the copper conductor is not efficiently used, however. The skin effect, in which current flowing through a conductor forces electron flow away from the centre of the conductor, causes current in a cylindrical conductor to concentrate near the surface of the wire, especially at higher frequencies.

In a planar transformer, the "windings" are actually flat conductive traces formed on copper-clad PCBs. In a flat conductor, the current tends to concentrate toward the outer edges and away from the centre, but current still flows through the entire conductor, albeit with improved overall current density compared to a cylindrical (wire) conductor. The end result is that a planar transformer, with its flat windings, can achieve higher efficiency at much smaller sizes compared to conventional wire-wound transformers.

Since Planar Transformers are constructed with windings fabricated on 4-oz. copper PCBs, they can be

manufactured with automated assembly equipment and superior unit-to-unit repeatability. Conventional transformers are manufactured with copper wire hand wound around ferrite cores. Variations can occur from differences between assemblers and even unit-to-unit differences from the same assembler caused by irregularities in the winding spacing. Automated assembly used in the manufacture of planar transformers helps to maintain repeatability and minimize parasitic reactance, such as inter-winding capacitance and leakage inductance. By minimizing parasitic contributions, high frequency ringing in a planar transformer's output voltage is minimized.

Uniformity and predictability of planar transformers also make them simpler to model than conventional transformers, when using computer-aided-engineering (CAE) tools such as SPICE to design a converter. Because of its construction --with conductive circuits stacked on dielectric sheets-- a planar transformer achieves good primary-to-secondary and secondary-to-secondary dielectric isolation. Once the circuit boards required to manufacture a planar transformer are designed and stamped, the windings remain at the same distance from each other, winding-to-winding and board-to-board. As a result, the performance of all transformers within one production run, and from one run to another, is extremely uniform. This repeatability makes the planar magnetic transformer ideal for high-volume applications requiring precisely matched performance. Planar transformers can simplify the power supply design task, since the performance they offer features low loss, repeatability, and predictability.

At higher current densities (and output power levels), 4-oz. copper may not be robust enough. Most circuit-board manufacturers offer heavier copper cladding, usually as a special order. Printed circuit boards can also be paralleled to double the wire size. Thermal paths should be carefully planned in a power supply design. A thermal path may require convection rather than conduction. When copper traces are buried under or near heat-producing equipment, dissipation of heat can be difficult. In any power supply design, isolation should be considered with regard to heat as well as electromagnetic fields.

5. POSSIBILITIES OF PARASITIC PARAMETER UTILISATION

There are three ways for modification of parasitic parameters of planar transformers for resonant converters:

- By placing the tracks of adjacent windings
- By separating the primary and secondary winding
- By adding a resonant planar inductor to the planar transformer

The first way is suitable for low power and highest frequency applications due to low achievable values of leakage inductance L_σ and inter-winding capacitance C_w . With vertically stacked windings, the magnetic coupling will be very strong and coupling factors close to 100 % can be achieved (Fig.4a). This layout will lead to low leakage inductance and to higher inter-winding capacitance. This capacitance can be reduced by projecting the tracks of a winding in between the tracks of the adjacent winding (Fig.4b). Furthermore, the repeatability of the capacitance allows for either compensating it in the rest of the circuit or using it in a resonant design. In the latter case, by placing the tracks of adjacent windings face to face a high capacitance could be chosen on purpose (Fig.4c) [2].

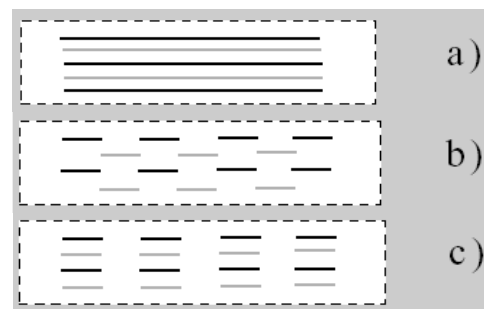


Fig. 4. Different winding designs

The second way is suitable for low power high frequency applications. A cross-section of a physical realisation of the planar transformer is shown in Fig. 5.

Due to the fact, that the leakage inductance of a transformer is mainly determined by the distance x between primary and secondary tracks the windings are divided on two PCBs to gain an adjustable leakage inductance. The transformer core is assembled as an E-E core instead of an E-PLT combination in order to get a larger range of adjustable inductance. A plot of the leakage flux for transformers with maximum and minimum separation of primary and secondary winding in rated mode of operation is shown in Figure 6a and 6b, simulated with the Maxwell 2D Field Simulator [3].

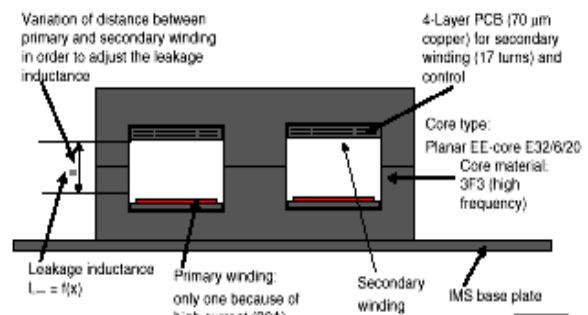


Fig. 5. Cross-section through transformer with adjustable leakage inductance [3]

The leakage inductance L_{σ} can be derived based on the magnetic energy density shown in Figure 6c and 6d. The simulation results match the measurements with an accuracy of 10%. The range of leakage inductance, which can be realised by separating the primary and secondary windings, is between 20 nH to 60 nH [3].

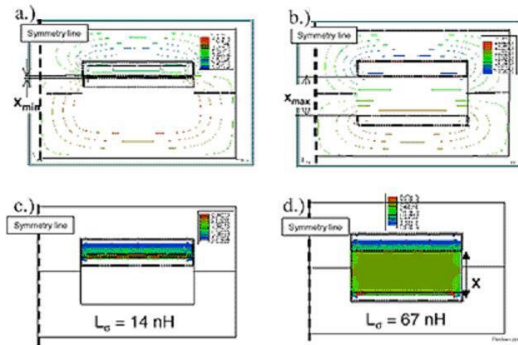


Fig. 6. A FEA Simulation results for determination of leakage inductance of the transformer for minimum (a) and maximum (b) distance between primary and secondary winding [3]

The third way is suitable for high power and also lower frequency applications. Planar magnetics are used in common mode chokes too. A special “six legs” planar ferrite core combined with a litz wire winding enables users to obtain a high quality factor (Q), (For example: $Q = 500$ of a $40\mu\text{H}/3\text{A}_{\text{RMS}}$ resonant choke at 1MHz) [3]. Instead of low loss power materials, high permeability ferrites are selected. There can also be an electrical advantage due to the geometry of the planar core compared with a standard shape. Inductance is proportional to the ratio of cross section to path length. The A_L values for the same cores that are compared for power handling in Table 1. The difference is dramatic, but the planar core is often enough limited because it has only half as much window area. That is a big disadvantage when the goal is high inductance, because inductance adds with the square of the turns. Otherwise, planar common mode chokes provide extremely high noise attenuation. It is possible to reduce their ratio of leakage inductance to self – inductance down to 0,005%.

Table 1. The effect of geometry on inductance Factor A_L [3]

Core	Style	A_c to l_c Ratio	Typical A_L (5000 μ material)	Window Area
E/E32	Planar	31 %	14 550	0.605 cm²
E2627	Traditional	13 %	5900	1.127 cm²

Due to the high self-capacitance, a planar common-mode choke can incorporate the input and output

capacitors in the choke itself. Thus, a planar common-mode choke can operate as a common-mode filter, with low losses that will allow operation at currents up to 200A.

6. APPLICATION

As example, resonant converter application is presented [4]. Because of dimensions and cost, two planar 3kW transformers are used in series from primary side and in parallel form secondary side. Primary sides are single, forming 700V input (2x350V) for series resonant converter output. Secondary windings of transformers are centre-taped and forms 30V 200A output. Output current is rectified by voltage rectifier (no filter inductor is used). The converter prototype is intended for railway wagon battery charging. Fig.7 shows transformers configuration in construction process. Fig.8 shows overall view of the converter.

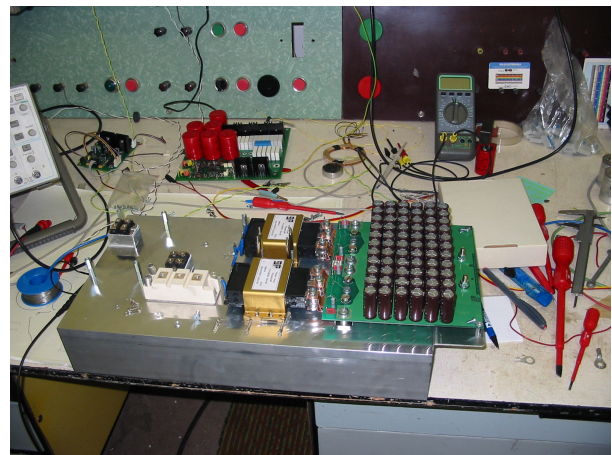


Fig. 7. Transformers configuration in construction process

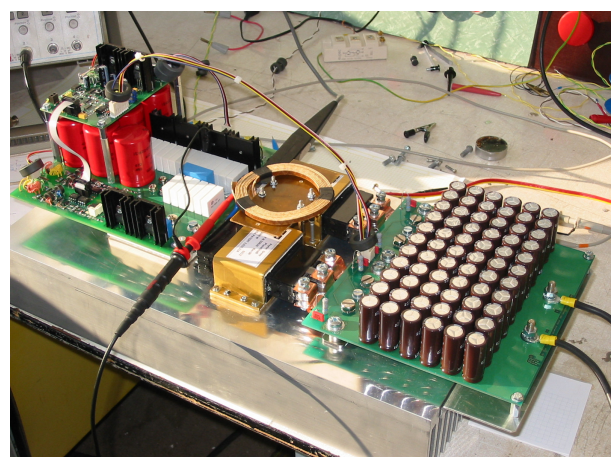


Fig. 8. Overall view of the converter

Fig. 9 shows typical sinus shape primary current and inverter output voltage at 700V input, 25V/160A output, while fig.10 shows the same conditions, however the resonant frequency is changed, PDM is lowered and output current of 90A is obtained. Switching frequency

varies from 20kHz to 90kHz with power ratio change 1:500. Deep ratio is achieved by unique patented technique. The method is based on resonant frequency changer. Transformers showed very good performance and robustness. A temperature increase is 10K at full power.

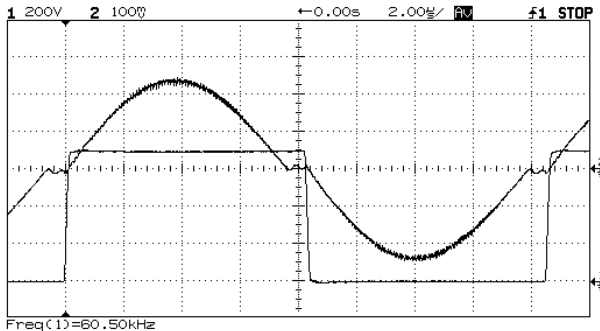


Fig. 9. Primary current and inverter output voltage at 700V input, 25V/160A output

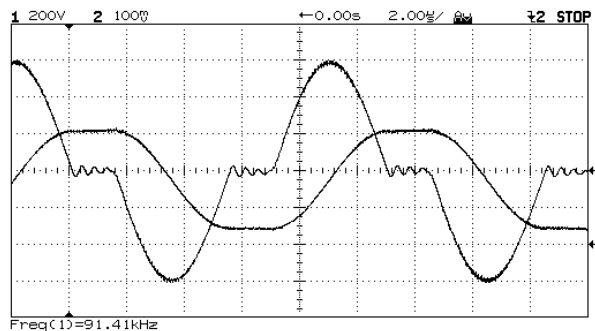


Fig.10. Primary current and inverter output voltage at 700 V input, 25 V/90 A output
ch.1: 200 V/d ch.2: 5 A/d

7. CONCLUSIONS

The transformer is a key element in any power-supply design. It was shown that, a planar transformer is more suitable for a soft switch – mode power supply designs like conventional wire wound transformer, because the planar magnetics provides higher efficiency, increased reliability, smaller size and lighter weight. Moreover, PM enjoy several benefits over their classical models, including up to 3 times the power density, superior repeatability, especially high reliability, superior heat dissipation, a 97 – 99 % efficiency without volume increase at a weight that's almost half that of classical magnetics. Planar transformers offer more possibilities of parasitic parameter modification and utilisation than classical models, in resonant converters. Planar magnetics are used in common mode chokes too. It's now also possible to design a planar common-mode choke, which can operate as a common-mode filter with low losses and will allow operation at currents up to 200A.

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