New Topology Eliminates Magnetic Cores at 50kHz NOT 50MHz!

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Abstract

This paper introduces new and disruptive technology to forever replace the perennial buck converter which has been the basic building block of Power Electronics Systems for the last 70 years! Speculations were made for decades that true advancement will be made by going to ultra-high switching frequencies, such as 5 MHz, so that the magnetic core used in the buck converter can be eliminated and a pure air-core inductor used instead. With that not taking place, the switching frequency which would enable that is subsequently moved to 50MHz. The new approach described herein is counterintuitive and surprising. The magnetic core for step-down voltage conversion can be eliminated even at 50kHz (kilohertz, not a misprint!) switching frequency, a factor of One Thousand Times (1000!) less than the above "dream" 50MHz frequency! What is needed to be accomplished is not some "dream come true" converter topology alone, but instead a completely new switching method, which, in turn, is enabling corresponding unique and novel topology!

The new Switching Method, named ***PWM-Resonant Method***, is based on using two resonances and yet regulating the voltage using the classical Pulse Width Modulated (PWM) variable duty ratio, constant switching frequency control. The present PWM switching method and its many True-Resonant and Quasi-Resonant variants simply will not do!

Buck converter fundamental flaws

Power Electronics was founded in 1950's based on the buck converter (**Fig.1**) despite its obvious flaw that inductor L is NOT an AC inductor but instead a "DC" inductor. This DC inductor must pass a full DC load current without saturating the magnetic magnetics core. Consequently, an air gap must be introduced into a flux path to drastically reduce the effective inductance and allow DC current flow. This inductance reduction is demonstrated in **https://youtu.be/uhc54pihAlk** Such reduction of the total inductance results in a very big size of the inductor, as illustrated by an RM 14 core used for 200W, 50kHz buck converter for a 5V, 40A inductor (**Fig 2**). The output capacitor C_o is equally large for this 12V too 5V voltage step-down example.

PWM-Resonant Switching Method and Unique Topology

The new PWM-Resonant Method can be best described with reference to the novel converter topology of **Fig. 3**. The converter features two complementary active switches operating out of phase with each other and at constant switching frequency and variable duty ration D of the main switch S_1. The two passive switches, diodes CR_1 and CR_2, operate in synchronism with related active switches to form two effective voltage bidirectional switches. Hence turning on S_1 switch turns ON the CR_1 diode. Likewise, turning ON S_2 switch turns ON diode CR_2.

New Topology with Two AC inductors New converter topology (Fig. 3) uses TWO AC inductors which eliminate the need for magnetic cores. In addition, the two AC inductors do not need the coil windings since the inductances needed to obtain PWM regulation are ***10nH*** each and could be implemented by use of piece of copper wire with 5mm length (**Fig. 4**). Most surprising and counterintuitive, is that the new converter is operated at only 50kHz switching frequency for a 200W, 12V to 5V, 40A as verified by simulation example explained in the later separate section. The most remarkable feature is also that the power throughput is only limited with the power capability of the switching devices and chip capacitors and is completely INDEPENDENT of the two AC inductors. Consequently, scaling to higher power is natural and not grossly limited in power and size with the single DC inductor of the buck converter. In fact, higher power is naturally leading to lower 25kHz switching frequency enabling a use of very high power GTO and/or IGBT devices at those frequencies.

Additional Advantages with all GaN devices

For low voltage applications, the two rectifier diodes are typically replaced with the synchronous rectifier MOSFETs in order to reduce the conduction losses. By use of the latest device technology, such as GaN, all four MOSFET devices could be replaced with GaN transistors. They could, in turn, be integrated on a single IC chip in a package usually used for a single low voltage HEXFET as illustrated in **Fig. 4**. GaN Devices have also an order of magnitude reduced parasitic capacitances. When they are operated at 50kHz instead of the 2MHz used for buck converter presently even a hard switching can be implemented with negligible losses and high efficiency.

Air-gap Effect on AC inductor: “DC” inductor!

The effect of the air-gap on inductance is demonstrated via “the moving viewgraph” of **Fig. 5**. By rotating the top viewgraph, the air-gap is simultaneously increased and the inductance decreased (slope of the flux linkages vs current characteristic in **Fig. 5**).

Experimental verification uses a ferrite Pot core type magnetic core with the screw in the middle as illustrated in **Fig. 6**. This enables to increase the air-gap continuously by varying the distance between the top and bottom half of the pot core.

The inductor is driven by the square-wave voltage (center-trace in **Fig.7**). The integral of that voltage is a time domain flux waveform (top trace in **Fig 7**), which does not have any distortion (pure triangular waveform). The bottom trace in **Fig. 7** is a time domain waveform of the measured current, which does show a distortion at the peaks of the current. This comes as a result of the nonlinear magnetization characteristic and nonlinear BH loop of the ferrite magnetic material as seen in **Fig. 7**.

The time domain flux waveform is then displayed as a vertical coordinate, while the current waveform is used as a time-domain horizontal component on an oscilloscope used with their X-Y coordinate option which eliminates the time to result in **Fig. 8**. Note the double valued characteristic of the BH loop, which appears to be “sheared” over from its nominal vertical position. Note that this demonstrates reduction of the inductance with increase of the -air-gap as anticipated in Fig. 5, but with actually displaying the loss characteristic of the ferrite material via a double-valued BH loop and finite width of the BH loop.

Note that the reduction of the inductance and decrease of the slope is the result of the increase of the air-gap. By looking at **Fig. 8**, one might, at first, interpret that this comes from some new soft magnetic material whose relative permeability is much smaller than 2000 of the ferrite material, like 50 to 100. However, this is not the case. When air-gap is reduced to zero, the flux vs current waveform will show a vertical BH loop characteristic of the ferrite material.

It is not surprising that DC inductor is physically very large as in **Fig. 2** and results in magnetic core material wasted resulting on the following deficiencies:

1. Manifold increase of the weight of the DC inductor.
2. Extra core losses reducing efficiency of the DC inductor.
3. Core saturation when the DC current is further increased beyond maximum it was designed for. This, in turns results in inductance decrease several times and proportionally increased output ripple currents and ripple voltages.

Three Myths of Power Electronics

Why has Power Electronics “dream” for decades been to eliminate the magnetics core by going to ever higher switching frequencies? This is one of three big myths which keep being touted as where the Power Electronics next big improvements should be made!

Unfortunately, the higher switching frequencies were at the same time ***hiding*** the fundamental deficiency of the buck converter: using an inductor, inherently an AC component, for passing DC current. The magnetic core increases AC inductance proportionally to the relative permeability of magnetic materials, so 3,000 for ferrite and 100,000 for Silicon Steel. Either magnetic material will saturate even in the presence of a minute mA DC current let alone 100A or more. Then air-gap comes to the rescue with insertion of an air-gap in magnetic flux path. While it does enables a large DC current to flow without core saturation it does so at the expense of “killing” inductance and very purpose of its use for effective filtering. It is obvious that such a component has very serious power limitations as even 200 DC ampere-turn’s, as example used in simulations confirms. This would then clearly demand very high switching frequencies to compensate for the loss of the inductance. This has led to the first myth:

Do We Need GHz Switching frequencies for Very High Power?

As most converter topologies were derived from buck converter, such as forward converter, full-bridge converter, boost and flyback converter, we reach to another myth propagated time and again:

Do We Need More or Have All Topologies Been Invented?

Finally, the magnetic components’ size and weight have been always by far dominating the overall weight and size of converters! Even high power switching device are very compact in comparison to magnetics components resulting in a third myth:

Power Supply on Chip (PwrSoC) vs Discrete Designs!

With the recognition of the deficiencies of the buck converter and the more general fundamental flaw of using an intrinsically AC inductor to artificially enable DC bias with air-gap insertions in present converters, the real probing question should be:

Do we need to continue using buck converter and its derivatives or should we discontinue all of them and look for much better solutions using innovative switching methods and topologies?

All three paradoxes are now successfully resolved by introduction of the innovative PWM-Resonant Switching Method and its novel topology of **Fig. 3** and **Fig. 9**.

DC Current Conversion Ratio

The measurement of the voltage conversion ratio as a function of the duty ratio D is displayed in **Fig. 10**. Note that for the converter has intrinsically a 2 to :1 voltage step-down. In particular example, the further voltage step-down is obtained for duty ratios bellow D= 2/3. At which point that happens is a design choice. Note also that for low duty ratio the step-down voltage follows linearly the operating duty ratio, like in a buck converter. The input current waveform and output current waveforms are displayed in **Fig.11**. Note that each of the two AC resonant inductors contribute their respective currents to the load, making the load current waveform, trapezoidal in nature. The direct benefit is that the AC ripple current is much reduced bellow DC current load and therefore the size of the output capacitance significantly reduced when compared to the buck converter. This leads to DC conversion ratio being controlled by reduced input current pulse due to reduced duty ratio D as in **Fig. 11**. Consequently, an opposite large DC voltage reduction ratio is obtained at low duty ratios as illustrated in measured DC voltage ratio in **Fig. 10**.

Ultra-High Efficiency

Another experimental prototype of a 750W, 100V to 50V, step-down converter was developed. The efficiency measurements shown in **Fig. 12,** demonstrated ultra-high efficiency over 99% over wide current range from 3A to 12A and nearly 99% at the full load of 15A.

Detailed Converter Operation

The converter features three resonant components: resonant capacitor Cr, resonant inductor Lr1 and resonant inductor Lr2. They, in turn create two OVERLAPPING resonances (**Fig. 13)**:

1. First resonance between resonant capacitor Cr and resonant inductor Lr1 (second trace)
2. Second resonance between the resonant capacitor Cr and resonant inductor Lr2 (third trace)

Note that full sinusoidal resonance is prevented and only positive cycle of each resonance is permitted due to current unidirectional feature of each diode rectifier. Hence, each resonance is starting at zero current level and stopping at zero current level as seen in the second and third trace of **Fig. 13**. This is the reason for an unmatched transient response illustrated in experimental verification in **Fig. 14**, where any DC load current transient is settled in one switching period. Moreover, there is no need for multiple stages as the load current (bottom trace in **Fig. 13**) has inherently low ripple current due to its trapezoidal current shape with a minimal AC ripple current.

Hence a much-reduced output filtering capacitor is needed to obtain a low output ripple voltage. Finally note the overlapping conduction of two resonant currents. This interval is characterized with the liner reduction of the resonant inductor current i_{r1} and the discharge of resonant inductor L_{r1} into the output.

No DC Current and Power Limitations

The most remarkable feature is that the power throughput is only limited with the power capability of the switching devices and chip capacitors and is completely INDEPENDENT of the two AC inductors. Consequently, scaling to higher power is natural and not severely limited in current capability, power and size as the buck. In fact, higher current requires more capacitors in parallel and smaller resonant inductors in order to keep the efficiency high. Increase of resonant capacitors value and decrease of resonant inductor values, both lead naturally to lower switching frequencies and not HIGHER switching frequencies. The reduction to 25kHz switching frequency, in turn could bring in the use of the very high power devices such as high power GTO and/or IGBT devices which can operate efficiently at lower frequencies and have much better utilization of Silicon and lower cost for given power. Additional unique performance features are made possible as shown next.

Transient Response Settles in a Single Switching Period

It should be noted that that each resonant current turns ON at zero current level and turns OFF at a zero-current level for ANY load current. In fact, the DC load current dictates the magnitude of each respective resonant current. The DC load current then DICTATES both magnitudes of the two resonant peak currents, which are by nature, always starting and ending at zero current level such as seen in **Fig.13**. It is not surprising then that the experimental measurements in **Fig. 14** shows that the large step-load current transient is settled in a single switching period and using only ONE converter module. Typical buck converters demand at least four and often up to eight converters operating in a parallel, which still results in inferior transient response. This is obviously due to an inherent DC energy storage in air-gap of each constituent buck converter module.

Simulation results

The converter of **Fig. 3** is simulated using the program PLECS from PLEXIM corporation. The simulation circuit for a 200W, 12V to 5V converter is shown in **Fig. 15** and input and output DC voltages in **Fig. 16.** The other key waveforms are shown in **Fig.17**, **Fig. 18** and **Fig. 19**.

Analytical model

In order to simplify analysis, the converter shown in Fig. 3 can be modified to version with a single resonant inductor L_r placed in series with the resonant capacitor C_r while the two other resonant inductors are shorted. The resonant circuit is then reduced to a single series resonant circuit consisting of the resonant capacitor C_r and resonant inductor L_r. The resonant equations are:

$$L_r \, di_r/dt = -v_r \qquad (1)$$

$$C_r \, dv_r/dt = i_r \qquad (2)$$

whose solutions are:

$i_r(t) = I_m \sin(\omega_r t)$ (3)

$v_r(t) = R_N I_m \cos(\omega_r t)$ (4)

where R_N is characteristic impedance, ω_r is radial frequency, f_r

resonant frequency, Δv_r resonant capacitor ripple voltage and I_{DC} is a DC load current given by formulas:

$f_r = 1/2\pi \text{ sqrt}(L_r C_r)$ (5)

$R_N = \text{sqrt}(L_r/C_r)$ (6)

$\Delta v_r = R_N I_m$ (7)

$I_{DC} = 2 I_m / \pi$ (8)

Current Scaling with PWM-Resonant Method

The conventional PWM switching method has only ***one*** variable and that is the switching frequency which is determined separately. The PWM-Resonant Method has in addition to constant switching frequency yet another well-defined frequency, the resonant frequency, the two being equal at 50% duty ratio. Note that the series resonant circuit has ***two*** variables which define the resonant frequency: the resonant inductor L_r and resonant capacitor C_r. This is the key for the following new *Current Scaling method*.

It is important to observe that the series resonant circuit must pass resonant inductor current given by (3) through both in resonant inductor and resonant capacitor. Let us now look how both components handle increased DC load current I_{DC} and consequently increased sinusoidal resonant current with corresponding peak I_m. In order to handle much increased current, resonant capacitor value must be proportionally increased so that a number of chip capacitors, each with given rms current capability, is able to handle it efficiently. On the other hand, just opposite is needed for the resonant inductor. It should have a smaller value and have a shorter length of the windings in order to carry higher current efficiently.

This points out that both resonant components are scaling in value in opposite direction to provide efficient solution**.** From resonant frequency definition (5) it is obvious that the scaling can be done in a such a way that the resonant frequency stays unchanged. Let us illustrate the natural current scaling law of PWM-Resonant Method via a numerical example. For:

L_r= 1μH and C_r = 1μF, we calculate f_r = 133 kHz (9)

but for ten times ***increased*** capacitor value and for ten times ***reduced*** inductor value we obtain the same resonant frequency:

L_r= 0.1μH and C_r = 10μF, we get the same f_r = 133 kHz (10)

The remaining question now becomes is how that change effects the ripple voltage Δv_r imposed on DC voltage of resonant capacitor C_r.

We now calculate the ripple voltage for two cases, initial case with I_m = 4A and when current is scaled ten times to 40A and get:

I_m = 4A R_N = 1Ω Δv_r = 4V (11)

I_m = 40A R_N = 0.1Ω Δv_r = 4V (12)

Note the remarkable result: the same voltage ripple is obtained in both cases. The resonant capacitor DC voltage for the simulated case of 12V to 5V is 6V. Thus, its time domain voltage will change from 4V to 8V.

Let us even go further and scale the current to 200A at 5V for 1kW converter by using another scaling factor of 10 in resonant component values and 5 times increased of DC load current:

L_r= 10nH and C_r = 100μF, we get the same f_r = 133 kHz (13)

I_m = 200A R_N = 0.01Ω Δv_r = 2V (14)

Conclusion: the same resonant and switching frequency is maintained and much reduced resonant inductor is made possible of only 10nH (nanoHenries!) and yet 1Kw power is processed! One argument could be made that a 100μF chip capacitor cannot handle 200A current. Not a problem: the resonant capacitor value could be increased by approximately 7 times to 700μF to increase the current capability 7 times. Yet, this will reduce both the resonant and switching frequency to 50kHz. Obviously, the higher power will be better handled at lower switching frequency. Even new devices, such as IGBT and GTO can be applied to great advantage at the reduced frequencies. This, once again, reconfirms that the higher power is handled naturally at proportionally lower switching and resonant frequencies and not the other way around as advocated by one of three Power Electronics myths: GigaHertz switching frequencies for very high power!

Power and Frequency Scaling Law Another myth propagated for decades is that the magic of higher switching frequency somehow makes possible increase of power processed. The physical reality is just the opposite: product of power and frequency should be constant or

Power x Frequency =Energy/Time= Constant (15)

This defines the physical reality that finite amount of energy is processed per unit of time. For example, if 10kW is processed at 1MHz switching frequency then processing 100kW at 100kHz should be just as challenging. Likewise doing 1 MW at 10kHz! Proposing even to process 1MW at 1MHz and not 1GHz is already well beyond being grounded on physical reality!

Comparison of buck and PWM-Resonant Ćuk at 50kHz

It is now very instructive to make the comparison with the buck converter operating at 50kHz for the same 200W, 12V to 5V, 40A step-down conversion. In order to easier follow the calculations, let us assume that the magnetic core used has 200mm^2 core cross-section, which is close to RM14 core shown in **Fig.2**. In order to get a reasonable AC flux density 5 turns should be used. Instead of actually calculating the air-gap needed to support 200 DC ampere-turns, we calculate the resultant inductance from:

$$L= NB_{DC}\, S/\, I_{DC} = 5 \text{ x } 0.1\text{T} \text{ x } 200\text{mm}^2 / 40\text{A} = 2.5\mu\text{H} \qquad (16)$$

Note that the inductance needed by buck converter for the same design is 250 times **higher** and yet there is no point in making a size and weight comparison with two 10nH inductors implemented with 5mm copper trace of PWM-Resonant Ćuk converter. Buck converter inductor will also have **additional** sizeable core losses despite its 5 turns as well as much larger copper winding losses so that comparison of losses is also pointless as is the cost comparison.

Buck Converter in Search for 20MHz Switching

Let us now see where did the demand for 25 MHz switching for buck converter come from? The "dream" was that, just by going to high enough switching frequency, the buck converter could finally shed its magnetic core and DC bias limitations and be used just as a coil without magnetic core! As the solution is already presented which employs just **two** small 10nH inductors, it would be instructive to see as to what switching frequency buck converter must operate to achieve that.

For 5V output and using 10nH inductor at 20MHz, the output ripple current of the buck converter would be 25A as per formula:

$$\Delta v = VD / (f_r\, L_r) = 5\text{V} \text{x } 0.5 / (10\text{MHz x } 10\text{nH}) = 12.5\text{A} \qquad (17)$$

The simulation results for the 5V, 40A shows the rms ripple current in output capacitor at 50kHz to be only 10Arms! Even a Four-hundred-fold (400!) increase in switching frequency from 50kHz to 20MHz is not enough to make buck converter competitive in size alone, never mind other performance characteristics!

Ceramic Chip Capacitors Paradox

I have invented 42 years ago, on April 1, 1975 a new converter which included for the first time a capacitive energy transfer in addition to inductive energy transfer that all other converters were solely based on. I named the converter originally Optimum Topology Converter (see my 1976 PhD thesis) to signify the importance of the interconnections and the topology name was launched. However, now some 40 years later attempts are made to rechristened this and mislabel it converter "architecture". Professor Middlebrook renamed my converter later as Ćuk converter due to many extensions, such as Coupled-Inductor, Isolated and Integrated Magnetics Isolated Ćuk converter. At that time, ceramic chip capacitors were used in conjunction with ferrite beads for filtering high frequency spikes and not for continuous current flow. They even lacked continuous rms current ratings. The only choice then was polypropylene capacitors which were flammable, large and expensive.

The current state of the art in ceramic chip capacitors is that there are capacitors rated for 7A at 150kHz in 2012 size having a footprint of 2.2mm by 1.2mm and 1.2mm height. Thus, paralleling a large number of them brings a high current capability in a very small volume and most important a very low cost. The buck converter and all its isolated derivatives do not include capacitors for energy transfer, but instead rely exclusively on inductors with DC bias and can be labeled as converters with inductive energy transfer ONLY. As shown above this led to the misleading 20MHz direction to reduce inductor size.

The new PWM-Resonant Method, shifted the power transfer burden completely to ceramic chip capacitors and two negligibly small, very efficient and low cost (only short copper strips) AC resonant inductors.

Power Supplies for Microprocessors

This application imposes a very demanding requirement on the transient response. At present, up to eight synchronous buck converters are used connected in parallel, phase shifted and operated at 1MHz in order to achieve fast transient and low ripple voltage on output. This paper demonstrated that even a single synchronous buck is inefficient, large and costly despite MHz switching speeds. Eight such converter also use 16 switching devices. The new PWM-Resonant Ćuk converter uses only 4 switching devices and yet results in much superior solution in all categories: efficiency, size, cost and transient performance!

Conclusion

Power Electronics has been for the last 60 years focused exclusively on the development of ever faster switching devices from 20kHz bipolar transistor through 200kHz MOSFET devices to present 2MHz GaN devices. In fact, it is precisely the availability of the high frequency switching devices which was, all along, ***hiding*** the fundamental flaws of the buck converter and ***delaying*** the inevitable conclusion: the buck converter should have been long ago ***retired***! Likewise, all DC-DC converters derived from buck converter, such as forward converter, full-bridge, as well as flyback converter carry over the same fundamental flaws of inductors with DC bias! Ironically, the development of faster switching devices became counterproductive and resulted in Energy Conversion System technology being completely neglected for over 50 years now. This is further evident in the present attempts to use a buck converter with GaN devices at 2MHz for a 48V to 1V, 100A, 100W conversion. The synchronous rectifier switch in buck is rated at 10kW yet delivers only 100W output! The alternative new ***system*** solution with the new Hybrid Switching Method and related new converter topology is described in the Video entitled: **What Comes First: Devices or Topology?** is at **https://youtu.be/0Tf-TlFKSZM**

This new coreless topology using judiciously two AC resonant inductors proves that the new switching method along with corresponding novel topology are the most important factors. Switching device requirements are then ***dictated*** by the new switching method and its sister topology and ***not*** the other way around as the case is now! The next video for my YouTube channel will be entitled:

What Comes First: Devices or Switching Method and Topology?

The new converter topology eliminates the need for a magnetic core at even the low switching frequency of 50kHz and results in an ultra-compact size and low weight. The new PWM-Resonant topology is naturally suited for scaling to very high power while maintaining small size and high efficiency. Single converter instead of multi-phase buck modules eliminates the large and fast DC load current transients in a single switching period making it ideal for driving microprocessors. A prototype using four MOSFET devices was built and performance verified as reported in US patent US 8,134,351 (see reference). This article demonstrates how four GaN switches could be integrated into a single IC chip, leading to a Power on Chip (PwrC) solution for a 200W, 12V to 2V, 100A replacement of the multi-phase buck converter. Synchronous buck converter for microprocessors and servers is at present a 10-billion-dollar industry in US alone. This new PWM-Resonant topology along with its all GaN device implementation on a single IC chip will make possible much improved power supplies for computer servers and data centers. However, this approach will also provide a much better solution for ***all non-isolated voltage step-down applications.***

Concluding Remarks

The name of this conference **Green Energy Conversion Systems (GECS)** perfectly describes the importance of Energy Conversion Systems, while Green in name underlines the ultimate importance of efficiency. The session named Advanced Power Electronics Converters (APEC), where this technical paper is presented, likewise emphasizes the key importance of the need for future additional Advanced Switching Methods and Topologies.

Acknowledgement

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Reference

Slobodan Ćuk,***" Four-Switch Step-down Storageless Converter"***, Patent No. US 8,134,351 B2, March 13, 2012.

Direct links of interest:

amazon.com/author/slobodancuk

www.youtube.com/slobodancukTESLAco

https://www.linkedin.com/groups/7045487.

teslaco.com

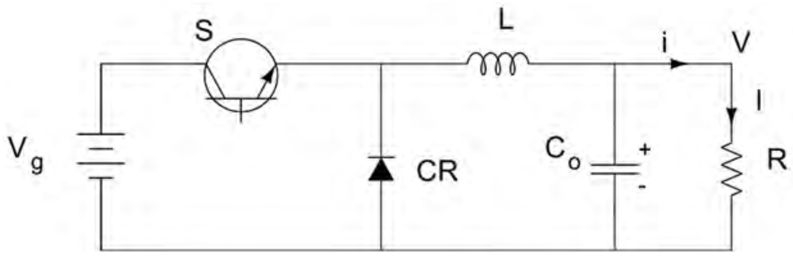


Figure 1

Figure 2

Synchronous Buck: Eight modules needed, large magnetic core, large size capacitors, low efficiency

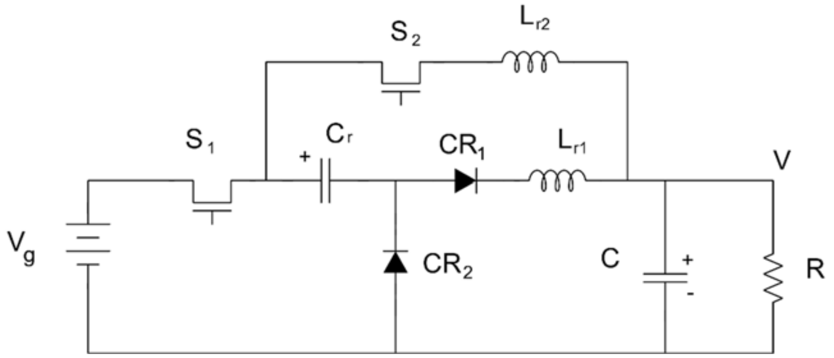


Figure 3

Figure 4

New Coreless Topology: Single IC chip with 4 GaN transistors. Single Module, One-Cycle Fast Transient, Power-on-a-Chip (PwrC) converter for 12V to 2V,100A

Fig. 5

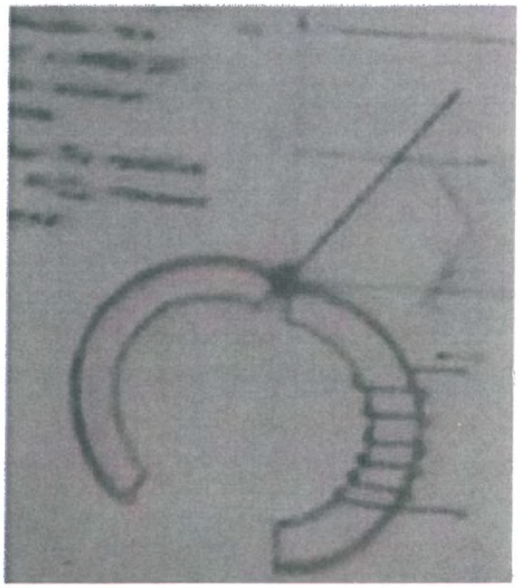


Fig. 7

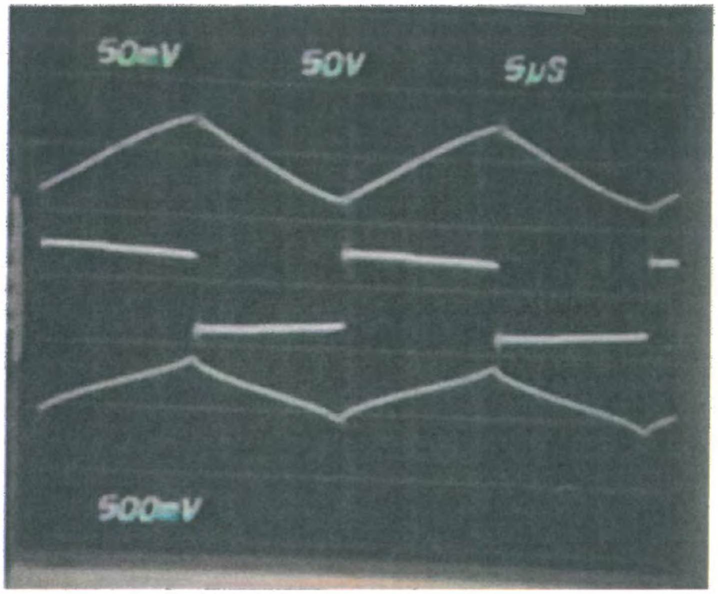
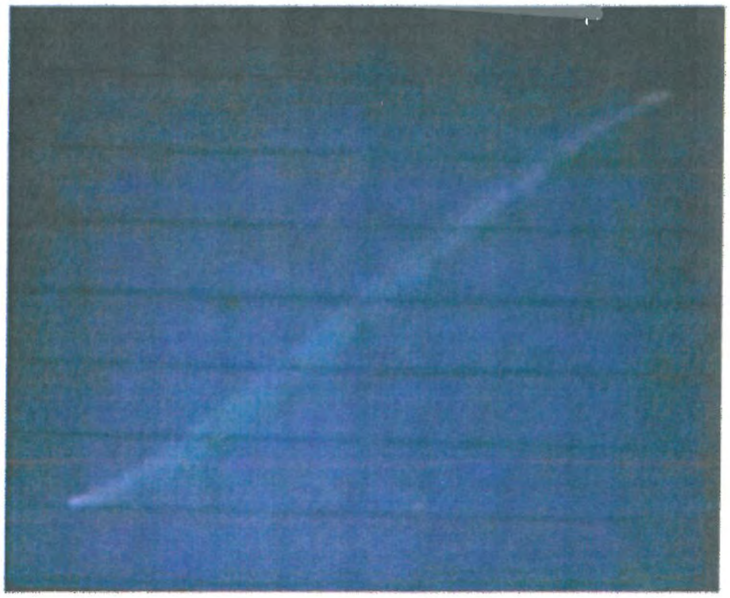
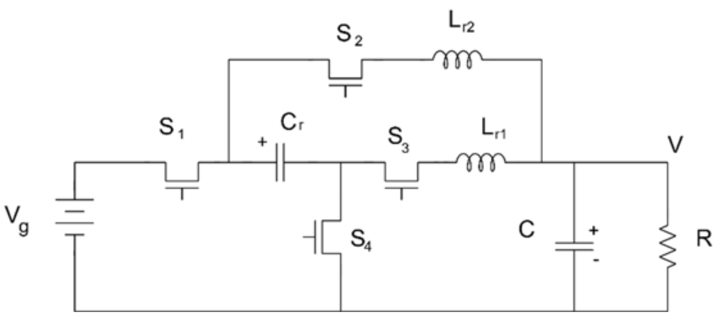


Fig. 6

Fig. 8



PWM-Resonant Ćuk converter, with two 10nH AC inductors at 50 kHz



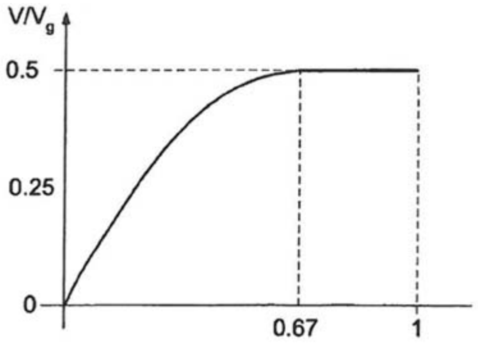
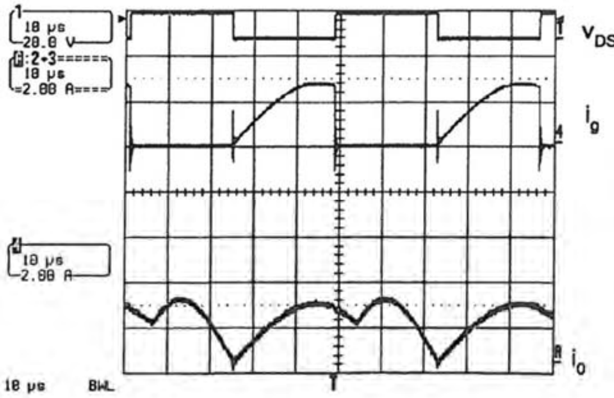


Fig. 9 All GaN implementation **Fig.10 Voltage ratio vs duty D**



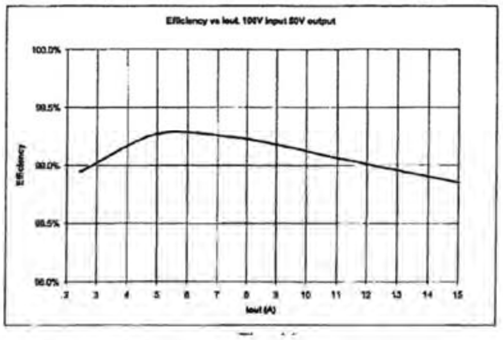
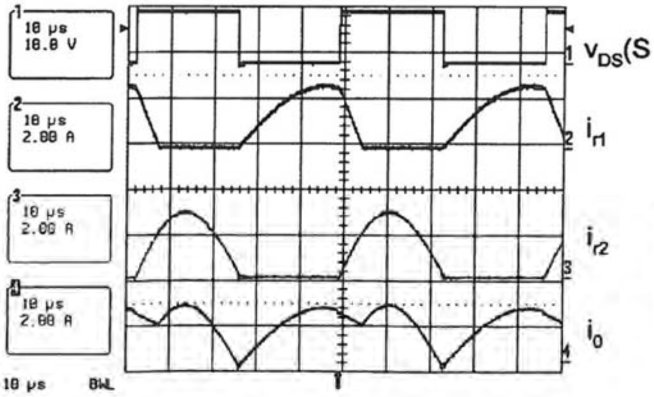


Fig. 11 input and output currents **Fig. 12 Efficiency measurements**



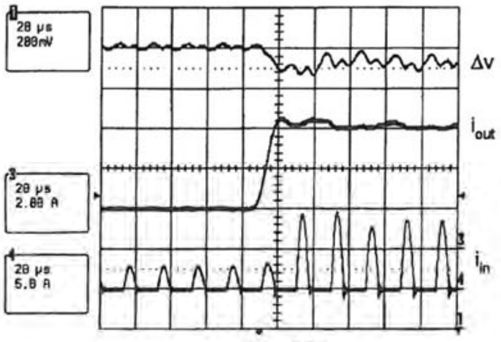


Fig. 39a

Fig.13 Resonant and output currents **Fig. 14 Transient response in one-cycle**

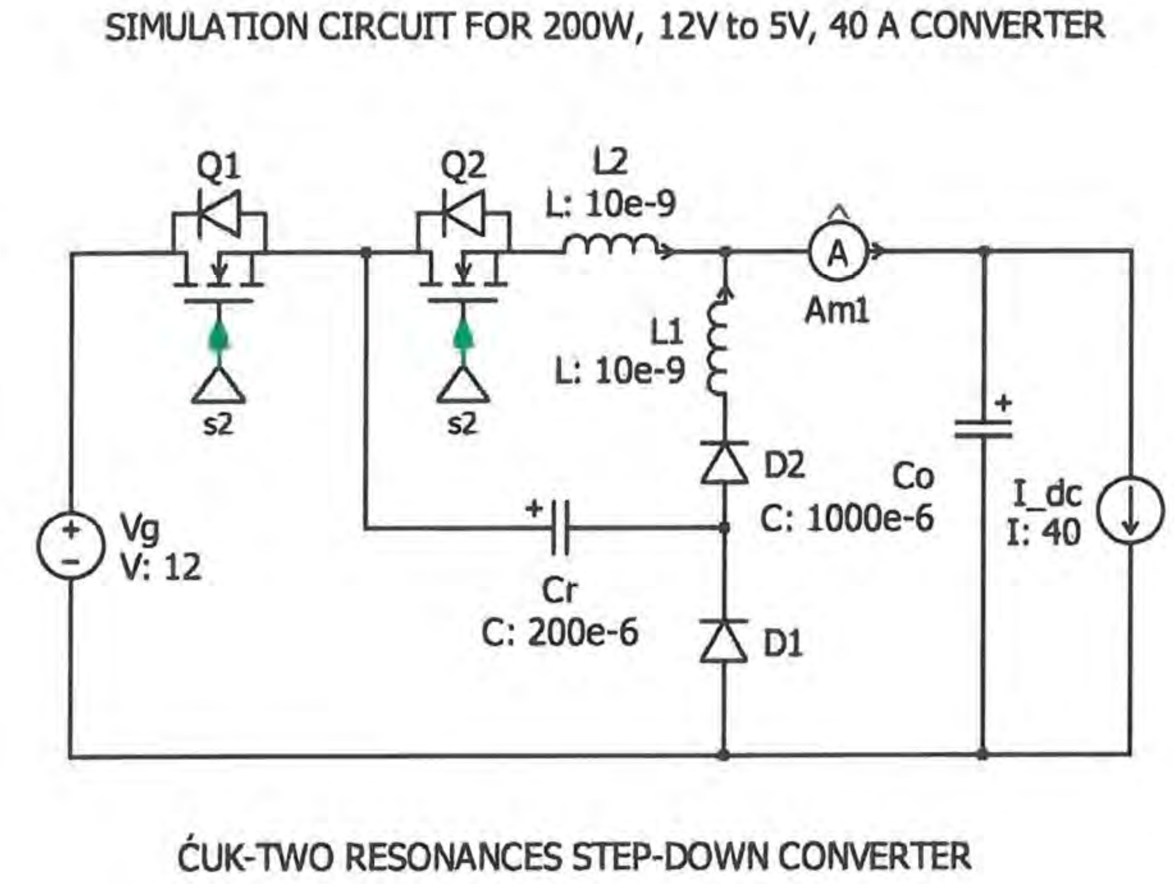


Fig.15 PWM-Resonant Ćuk Simulation using PLECS from PLEXIM.com

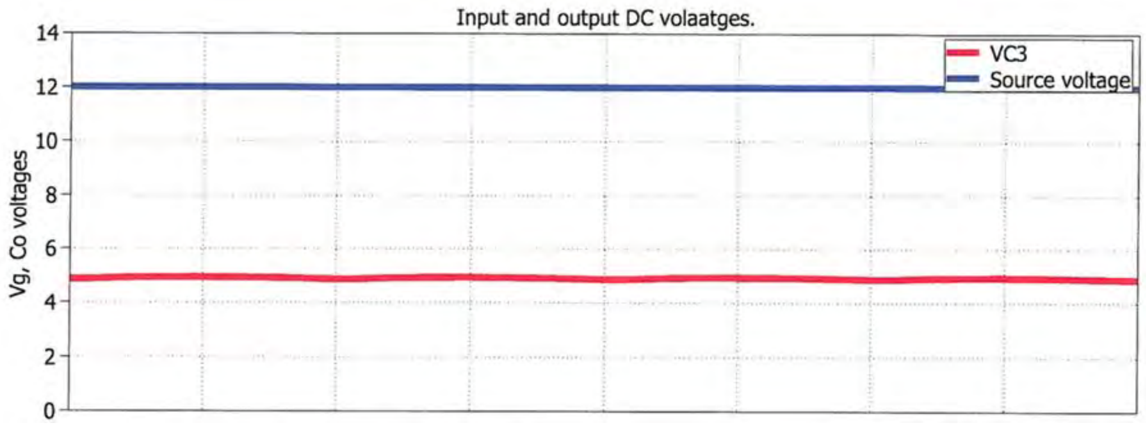


Fig.16 Input and output DC voltages for 12V to 5V, 40A converter

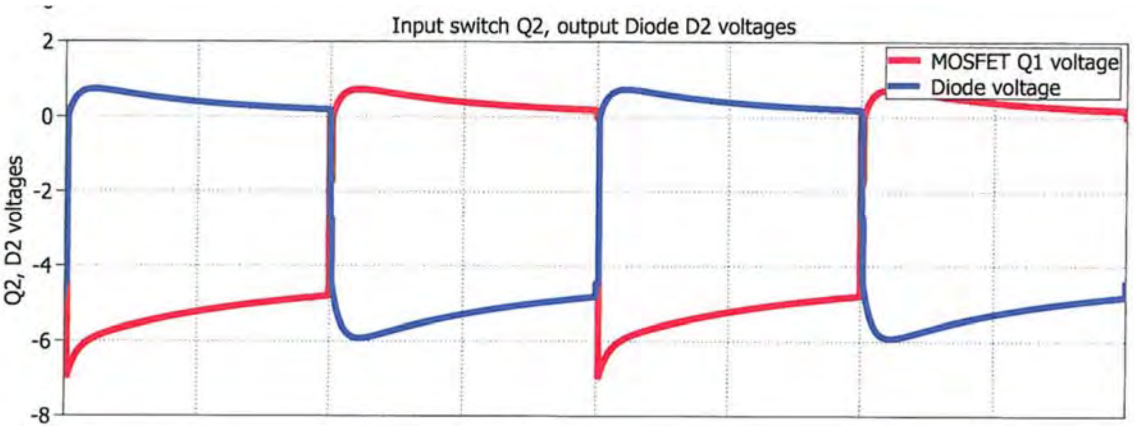


Fig.17 Diode voltages

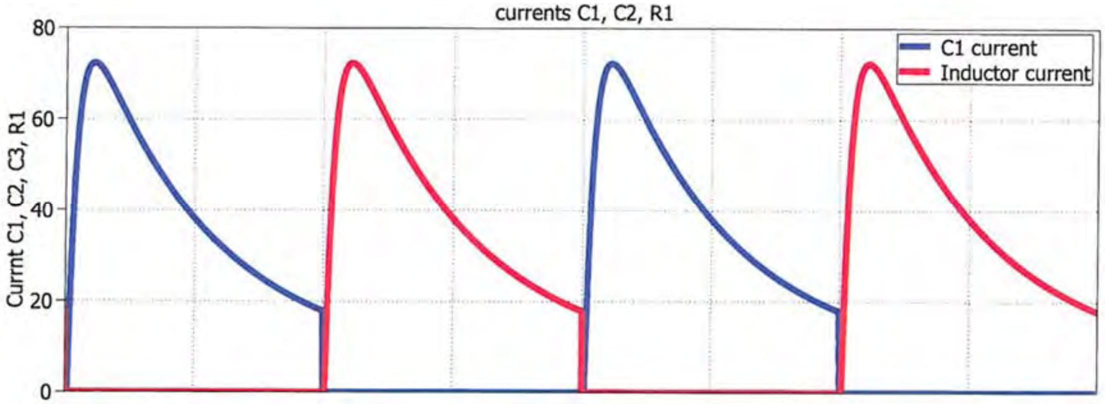


Fig. 18 Diode Currents

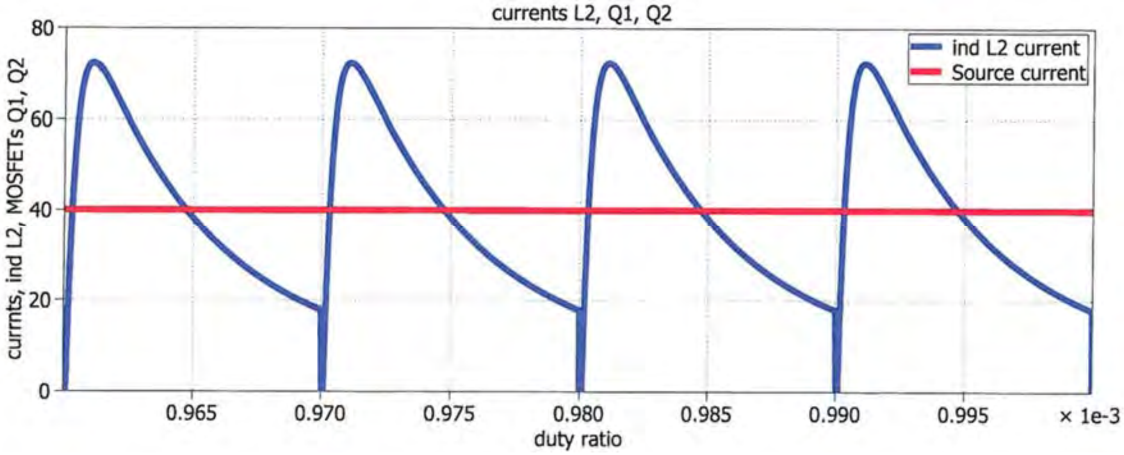


Fig 19 Output DC current and superimposed AC ripple current