Ceramic capacitor controlled resonant LLC converters

Ido Kolberg
School of Electrical Engineering
Tel Aviv University
Tel-Aviv, Israel
idokolberg@mail.tau.ac.il

Doron Shmilovitz
School of Electrical Engineering
Tel Aviv University
Tel-Aviv, Israel
shmilo@post.tau.ac.il

Shmuel (Sam) Ben-Yaakov
Department of ECE
Ben-Gurion University
Beer Sheva, Israel
sby@bgu.ac.il

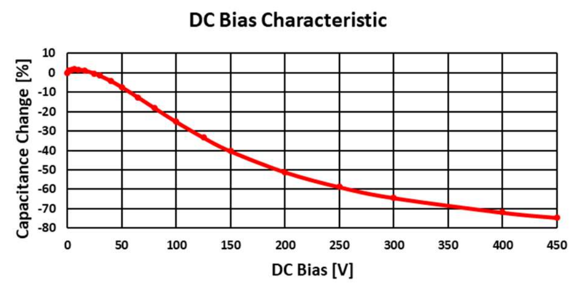
***Abstract*— The possibility of applying standard commercial ceramic capacitors for controlling a resonant LLC converter was studied analytically and experimentally. Using a two serially connected ferroelectric capacitors assembly, experiments were run on a mockup of an LLC converter that was switched at 90kHz to a power level of 5W. The voltage dependent capacitors had a range of 95nF-320nF for a bias span of 0-100V. A DC bias driver with a high output impedance that is suitable for controlling the voltage dependent capacitors is proposed and discussed. The theoretical considerations and experimental results of this study suggest that ferroelectric ceramic capacitors could be a viable control element of resonant LLC converters running at a fixed switching frequency.**

Keywords— Resonant converters; DC-DC converters; resonant LLC converter; Ceramic Capacitors; Voltage dependent capacitors

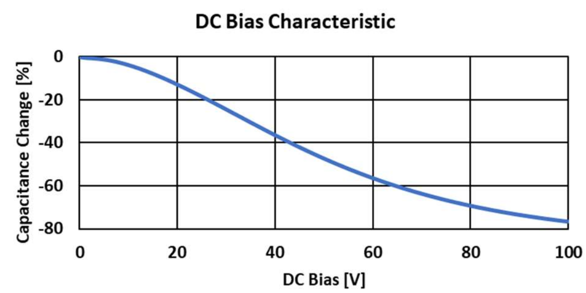
I. Introduction

Ceramic capacitors (CC) are being used extensively in power electronics circuits as they have a multitude of advantages that match power conversion circuits requirements. Having a high dielectric constant, the CC are of small size and by proper design they can withstand high voltages [1-4]. Furthermore, they have a relatively low equivalent series resistance (ESR) and are compatible with high switching frequencies to about 10MHz. And finally, the CC are relatively inexpensive and thus compatible with current cost-effective design trends. Notwithstanding the many advantages of the CC, they do suffer from two basic problems: temperature dependence and bias voltage dependence. The latter will cause the capacitance to drop as the voltage across the capacitor increases. Some CC dielectric materials, notably the Class I C0G is temperature stable and some CC dielectrics material are relatively insensitive to bias voltage. However, small size ferroelectric CC of Class II and Class III which have a high dielectric constant material, like Y5V, are extremely sensitive to bias voltage [2]. Fig. 1 depicts the bias voltage dependence of the commercial CC that were used in this study.

The capacitor CGA9P4X7T2W105M250KE (TDK) is a 1μF, 450V capacitor of material X7T, while GRM31MR72A474KA35L (Murata) is a 0.47μF, 100V, X7R capacitor. Both drop to about 25% of their initial capacitance value at their specified maximum voltages. The problem of voltage dependence of CC has been lingering designers since the introduction of commercial CC. The bias dependency problem is usually "solved" by specifying larger capacitances such that the required capacitance will be assured at the operating point.



(a)



(b)

Fig. 1. *Voltage dependency of experimental CC (a) TDK, CGA9P4X7T2W105M250KE. (b) Murata, GRM31MR72A474KA35L*

In this preliminary investigation, we examine the possibility using voltage dependent CCs as a control element in resonant LLC converters [5-10]. The use of CC to control other resonant converters has been investigated to some extent in the past [11-15]. A method for controlling an LLC converter by a controllable capacitor was suggested earlier [16]. However, the device used in that study was a bank of capacitors of a binary ratio connected via switches to obtain a variable capacitance value. The advantages of the CC controlled LLC converter (CCLLCC) proposed here, is infinite resolution (limited only by the noise level), small size, fast response (with proper voltage drive) and the possibility to run at a fixed switching frequency. The primary objective of this study is to characterize the CCLLCC and to examine the envelope of performance possible with it.

978-1-5386-1180-7/18/$31.00 ©2018 IEEE

II. CAPACITOR CONTROLLED LLC COVERTER (CCLLCC)

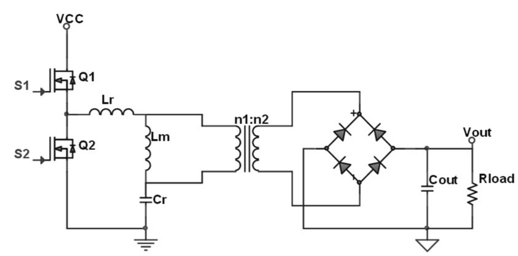
The classical approach to control an LLC converter (Fig. 2a) is by a variable frequency. The generic configuration of Fig. 2a is the half bridge version with transformer isolation between input and output. In this scheme, the transformer is assumed to be ideal while in practice Lm will be the inductance of the transformer's primary winding. The small signal, input to output voltage ratio, $V_{oac}/V_{in_{ac}}(f_s)$ is traditionally obtained by analyzing the small signal equivalent circuit (Fig. 2b) [17]. The voltage transfer ratio of the linearized circuit is:

$$\frac{V_{o_{ac}}}{V_{in_{ac}}}(f_s) = \frac{F_x^2(m-1)}{\sqrt{\left(m\cdot F_x^2-1\right)^2+F_x^2\cdot\left(F_X^2-1\right)^2\cdot(m-1)^2\cdot Q^2}} \quad (1)$$

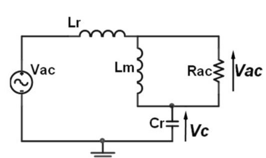
Where: $f_s = switching\ frequency;\ Q = \frac{\sqrt{L_r/C_r}}{R_{ac}};$

$$R_{ac} = \frac{8}{\pi^2}\cdot\frac{N_p^2}{N_s^2}\cdot R_{load};\ F_x = \frac{f_s}{f_r};\ f_r = \frac{1}{2\pi\sqrt{L_r\cdot C_r}};\ \ m = \frac{L_r+L_m}{L_r}$$

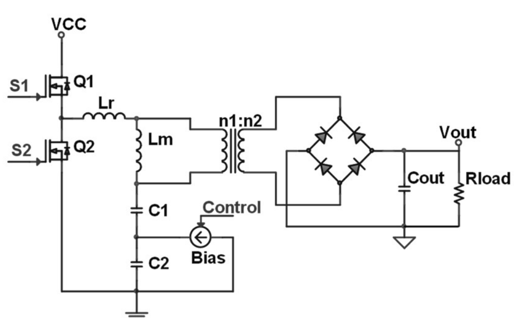
Typical small signal gain curves of the classical LLC converter with Q as a parameter are shown in Fig. 3a and the phase of the input voltage is given in Fig. 3c.



(a)

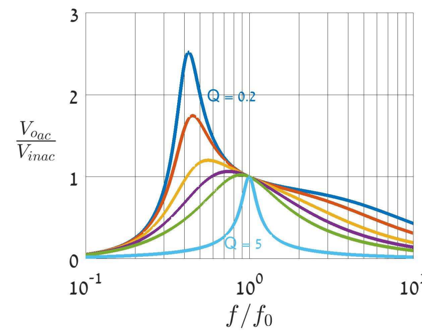


(b)

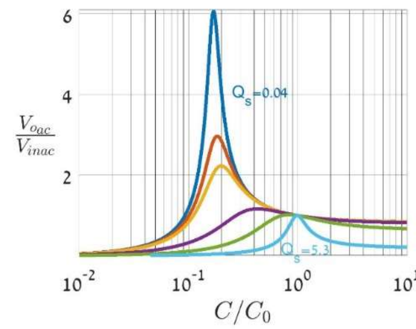


(c)

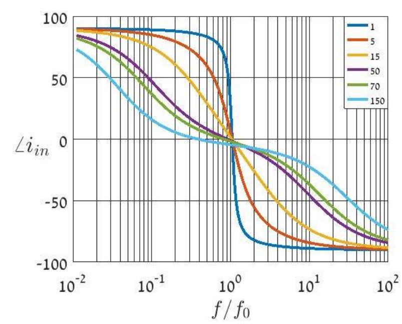
Fig. 2. *The LLC. (a) Classical circuit. (b) Small signal equivalent circuit. (c) Proposed CCLLCC.*



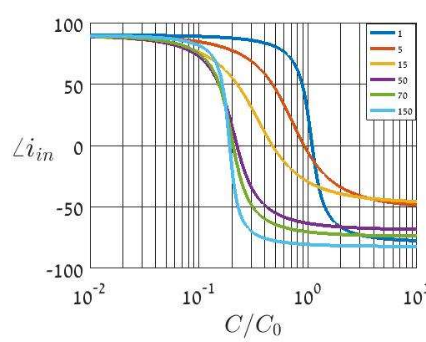
(a)



(b)



(c)



(d)

Fig. 3. *Small signal response of an LLC. (a) Gain of frequency . controlled LLC converter. (b) Gain of CC controlled converter. (c) Phase of frequency controlled LLC converter.(d) Phase of CC controlled converter .*

The structure of the proposed CCLLCC is similar to the basic LLC converter (Fig. 2a) except that it is driven by a fixed frequency and includes a voltage dependent ceramic capacitor C2 that is connected in series with a second capacitor C1, (Fig. 2c). C1 is required to block the DC path from the bias source to the half bridge. The bias drive is fed to the midpoint between the capacitors. The serially connected capacitor C1 could be a fixed capacitor or also a voltage dependent capacitor as C2, as was done in this study. It should be noted that the DC bias of C1 is different from that of C2 since the former is also exposed to the average output voltage of the half bridge. The DC bias source needs to have a high output impedance so not to load the resonant network (details of the proposed driver are given below).

The small signal voltage gain of a CCLLCC (2), based on the first harmonics approximation circuit of Fig. 2b, was derived from (1) by assuming a fixed switching frequency f_s while the independent variable is the total capacitance C (C_1 in series with C_2) normalized to a reference capacitance C_o ($\mathbb{C}$) defined below

$$\frac{V_{o_{ac}}}{V_{in_{ac}}}(\mathbb{C}) = \frac{\mathbb{C}(m-1)}{\sqrt{(m\cdot\mathbb{C}-1)^2+\mathbb{C}\cdot(\mathbb{C}-1)^2\cdot(m-1)^2\cdot Q_s^2}} \quad (2)$$

$$\text{Where: } C_0 = \frac{1}{4\pi^2 L_r f_s^2}\ ;\ \mathbb{C} = \frac{C}{C_0}\ ;\ Q_s = \frac{\sqrt{L_r/C_0}}{R_{ac}}$$

The normalized voltage gain ratio of the linearized CCLLCC converter is given in Fig. 3b and the phase of the input voltage is depicted in Fig. 3d with Qs as a parameter. It can be observed that the general shape, and in particular the equal gain point is very similar to the classical LLC converter behavior (Fig. 3a). However, visual comparison of the Fig. 3a and 3b could be misleading since the definition of Qs is different from that of Q. Moreover, the value of the traditional $Q, \sqrt{L_r/C}/R_{ac}$, of the CCLLCC is not only a function of Rac but also of the variable control parameter C.

The phase plots (Fig. 3c, 3d) show that in the two converters the phase of the sources' currents is lagging with respect to the input voltage at frequencies which are higher than the resonant frequency for each given Q or Qs. This implies that operation at these phase lag regions will facilitate zero voltage switching (ZVS). However, there are notable differences between the two phase plots. In the classical LLC converter, the inflexion point of the phase is around the resonant frequency for all of the Q values. In the CCLLCC, the inflection point is different for each Qs. This is because a change of C is associated with a change in the resonant frequency of the network. This difference may call for somewhat different design rules as compared to those of the traditional LLC converter. Additional research is required to delineate this issue.

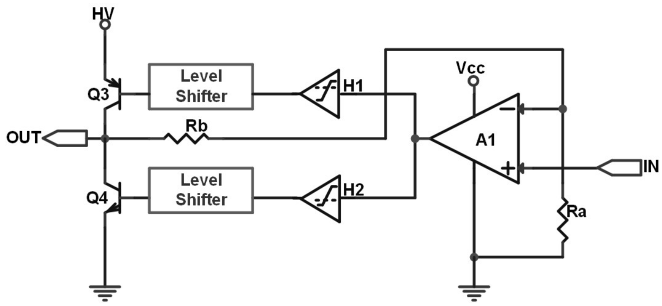
The proposed control method of the CCLLCC requires a means for biasing the capacitor at a DC voltage that will provide the required capacitance. Since the injection point is between the two serially connected capacitors (Fig. 2c) the resistance seen is very high and theoretically, once a charge is delivered, the capacitors will maintain the potential indefinitely. It is thus clear that the power enquires to drive the DC bias is infinitesimal, save the power consumption of the driver. The driver must have a high output impedance in order for it not to load the capacitors. The proposed driver, whose block diagram is shown in Fig. 4a and the more details topology in Fig. 4b, fulfills this requirement by having the collectors of BJTs at its output. These output BJTs are driven by level shifters that have a dead band provided by Z1 and Z2 to prevent a shoot through current through the BJTs. By this the power consumption of the driver is minimized. And yet, when required, the driver can output a high (design dependent) current to quickly move the bias voltage from one value to another as might be needed during a transient state of the CCLLCC.

The operation of the driver could conceivably be in open loop while the overall control will be based on an outer feedback loop. However, this might add some parasitic phase delays which could render the system to be unstable. To prevent this, the proposed driver works in closed voltage-feedback loop (R_a, R_b in Fig. 4a) while maintaining a high output impedance at the switching frequency. This is accomplished by extra phase shaping to override the lowering of its output resistance by the voltage-feedback - at the switching frequency range. This is accomplished by C1 (Fig. 4b) that lowers the open loop gain at the desired frequency range. Further phase shaping is provided by C1, R4 and C2, R5, to ensure stable operation of the driver. The output resistance of the driver at the switching frequency will be in the order of magnitude of R2. Hence, R2 should be chosen such that its resistance is several orders of magnitude larger than the impedance seen at the midpoint between the capacitors.

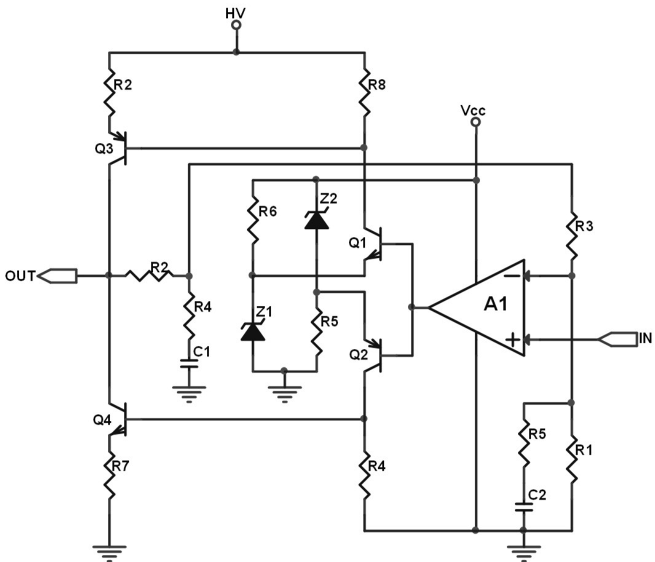
The bias voltage set by the driver (V_{OUT}) affects the two serially connected capacitors C1 and C2 (Fig. 2c). Assuming a symmetrical drive of the half bridge (Fig. 2a), the voltage of C1 will be V_{OUT} while the voltage on C1 is (V_{OUT}-Vcc/2), assuming a duty cycle of 50%. The total capacitance of the serially connected capacitors can be obtained from the data of Fig. 1a & 1b. The results are shown in Fig. 5 for the bias range of 0-100V, the upper limit of the experimental C2. Fig. 5 reveals that the capacitance range of the experimental CC package is 95nF-320nF, or +/- 50% around a center value of 200nF. Comparison of this range to the small signal responses of Fig. 2b, 2d suggest that the practical capacitance range that can be achieved, as exemplified in the private case of this work, is compatible with control requirement of the CCLLCC. Optimization of the control and the selection optimal commercial CCs are beyond the scope of this paper.

III. CAPACITORS LOSSES

A limiting factor of the power level that can be achieved by the proposed CCLLCC is the power dissipation of the voltage dependent capacitors. It should be pointed out in this connection, that the temperature effect on the capacitance is less important in this case (unless of course the temperature dependence is very large), since the variable capacitors will operate in closed loop. Figs. 6a, 6b are the ESR data provided by the manufacturers for the experimental capacitors. The normalized ratio of the two ESRs at around 100kHz is about 1.5: the ESR of C2 (0.47µF) is about 30mΩ while that of C1 (1µF) is about 10mΩ. Realistically, these capacitors can carry currents in the order of 2-3Arms. No survey was made as yet to select capacitors which



(a)



(b)

Fig. 4. *DC bias driver. (a) Block diagram. (b) Proposed topology*

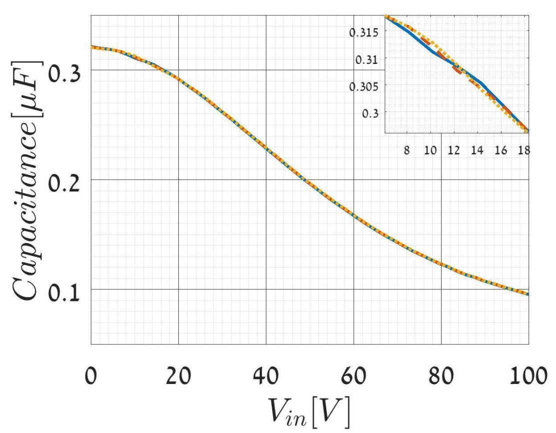
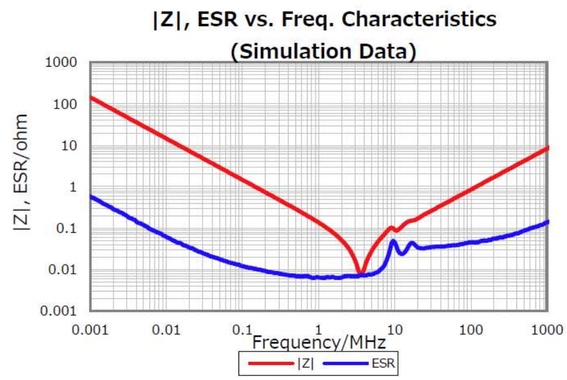
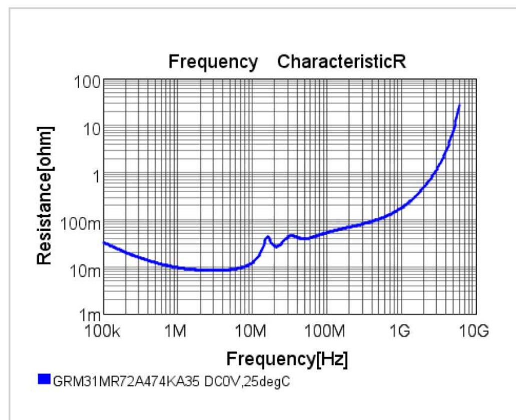


Fig. 5. *Capacitance control range of the ferroelectric CC assembly used in this study. Superimposed graphs for Vcc=20V, 25V, and 30V.*



(a)



(b)

Fig. 6. *ESR of experimental capacitors. (a) CGA9P4X7T2W105M250KE. (b) GRM31MR72A474KA35L*

are, on the one hand, sufficiently voltage dependent to control an CCLLCC, and on the other, have a low ESR. In any event, the power dissipation of the capacitors sets a boundary to the CCLLCC power level as in the case of film capacitors. The ESR of ferroelectric ceramic capacitor is in the order of magnitude of the ESR of film capacitors so capacitor power dissipation is not a unique problem of the CC. One way to extend the power level boundary is to increase the capacitance of the capacitors. This

could be done in two ways: lowering the switching frequency or keeping the frequency value but changing the characteristic impedance. Each approach has its own deficiencies. Lowering the switching frequency implies a larger isolation transformer and higher ripple at the output for same filter capacitor. Lowering the characteristic impedance requires a readjustment of the reflected Rac (Fig. 2b) to maintain the quality factor Q. Further research is clearly required to sort output these options.

IV. EXPERIMENTAL

The performance of the CCLLCC was tested experimentally on the equivalent CCLLCC depicted in Fig. 7. The circuit parameters were as follows: Lr = 8.86μH ; Lm= 43.3μH ; C1= 1μF 450V (TDK CGA9P4X7T2W105M250KE) capacitor of material X7T; C2= 0.47μF 100V (Murata

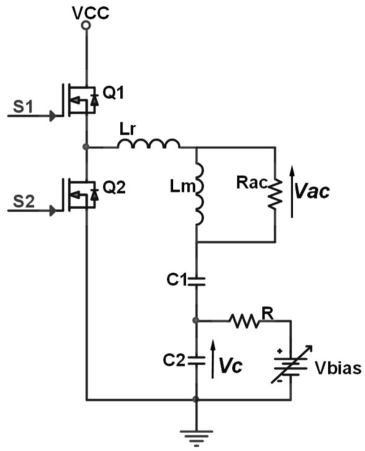


Fig. 7. *Experimental CCLLCC.*

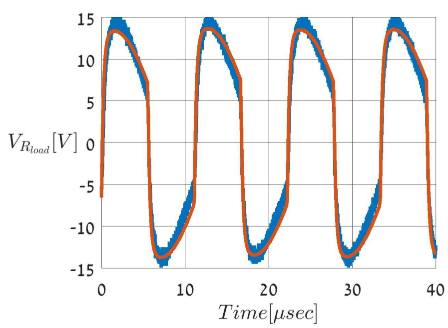
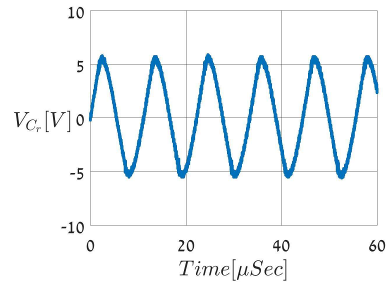


Fig. 8. *Comparison of measured output voltage of CCLLCC to the simulated voltage of an LLC converter with fixed capacitor. Rac=33Ω ; Vin=23V; C@48Vbias=201nF; fs=90kHz*

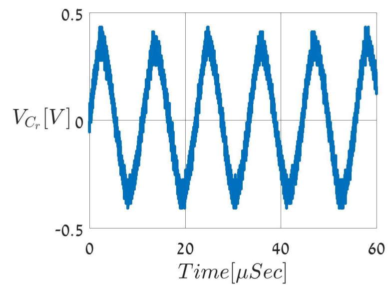
GRM31MR72A474KA35L) capacitor is of material X7R ; fs=90kHz ; nominal output power =5W with V_{CC}=23V and R_{ac}=33Ω . The half bridge driver was UCC27201AEVM-328. The voltage bias range was 0-100V. The bias was adjusted by a laboratory DC power supply which output was connected to the midpoint of capacitors C1, C2, via a large resistor (Fig. 7), R=2MΩ.

The experiential results reveal that the basic waveforms of the CCLLCC were practically identical to the waveform of an LLCC with fixed capacitor as obtained by simulation. An example is given in Fig. 8.

The control range of the CCLLCC was tested by loading the circuit with resistors in the range 15Ω to 150Ω for a target output voltage of 11Vrms. The measured capacitor voltage (Fig. 9a, 9b) was as expected in a classical resonant LLC converter. It would appear that the nonlinearity of the CC does not introduce any appreciable distortion. This is probably due to the narrow bandwidth nature of the resonant network of the LLC topology. ZVS was achieved in all cases. The waveform of Fig. 9a shows an AC voltage of about 11Vpp across the capacitors. Since the input voltage was 29.5V and the bias was 14V the total capacitance (Fig. 5) was 300nF. This implies that the capacitors current was about 0.73Arms. Hence, from Fig. 6, the power

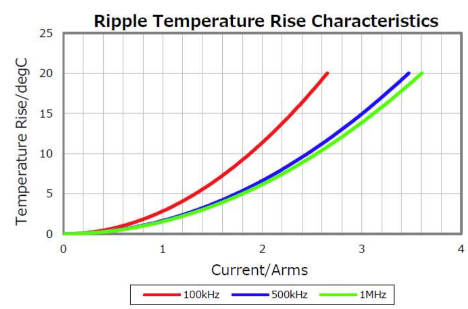


(a)

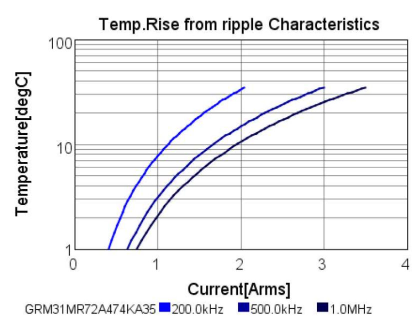


(b)

Fig. 9. *Experimental ac voltage of the serially connected C1, C2, capacitors (a). DC bias: 14V; 15Ω load; Vin=29.5. (b) DC bias: 100V; 50Ω load; Vin=18.6V.*



(a)



(b)

Fig. 10. *Temperature rise data provided by the experimental CC manufacturers.(a) CGA9P4X7T2W105M250KE. (b) GRM31MR72A474KA35L*

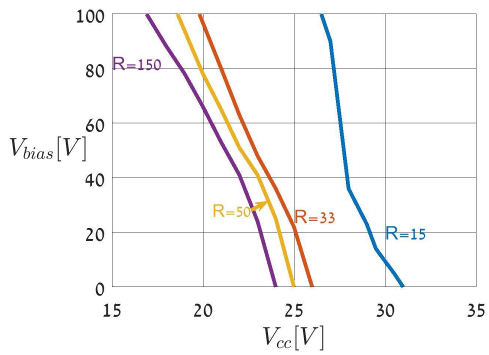


Fig. 11. *Experimental bias voltage required to maintain an output voltage of 11V with load resistors (from left to right): 150Ω , 50Ω, 33Ω, 15Ω.*

dissipation of C2 was about 16mW and the power dissipation of C1 was about 5.3mW. Applying the temperature rise data provided by the manufacturers (Fig. 10) the expected temperature rise for C1 is 2.5Ω while that for C2 is ~6-10℃.

The results of the experiments, summarized in Fig. 11, reveal that the experimental circuit can maintain the nominal output voltage of 11Vrms of loads in the range 33Ω to 150Ω over the input voltage range of 20V–24V with a voltage bias range of 0-100V. The 15Ω experiment is clearly an outcast as it is outside the control range of the experimental CCLLCC. Under the experimental conditions, the 33Ω load translates into Qs= 0.159 while the 150Ω corresponds to Qs= 0.035.

V. CONCLUSION

The viability of applying a standard commercial CC for controlling resonant networks was studied analytically and examined experimentally. The results of this study show that the CC could effectively control a resonant LLC converter running at a fixed excitation frequency. It was found that the required capacitance span in the CCLLCC to match the load range of the traditional frequency controlled resonant LLC converter, can be easily achieved with commercial CCs and that the non-linearity of the CC has only a marginal effect on the converter's operation.

REFERENCES

[1] S. Scheier and S. Frei, "Characterization and modeling of ESD-behavior of multi-layer ceramic capacitors," in *Proc. 2013 International Symposium on Electromagnetic Compatibility*, 2013, pp. 1028-1033.

[2] O. Dejean, T. Lebey and V. Bley, "An experimental characterization of nonlinear ceramic capacitors for small and large signals," *IEEE Transactions on Components and Packaging Technologies*, vol. 23, no. 4, pp. 627-632, 2000.

[3] L. Dai, F. Lin, Z. Zhu and J. Li," Electrical characteristics of high energy density multilayer ceramic capacitor for pulse power application," *IEEE Transactions on Magnetics*, vol. 41, no. 1, pp. 281-284, 2005.

[4] S. Kwon, W. Hackenberger, E. Alberta, E. Furman and M. Lanagan, "Nonlinear dielectric ceramics and their applications to capacitors and tunable dielectrics", *IEEE Electrical Insulation Magazine*, vol. 27, no. 2, pp. 43-55, Mar. 2011.

[5] H. Yusuke, T. Hajime, I. Toshifumi and M. Akira, "Contactless DC Connector Based on GaN LLC Converter for Next-Generation Data Centers", *IEEE Transactions on Industry Applications*, vol. 51, no. 4, pp. 3244- 3253, July. 2015.

[6] C. Armbruster, A. Hensel, A. Wienhausen and D. Kranzer, "Application of GaN power transistors in a 2.5 MHz LLC DC/DC converter for compact and efficient power conversion", in *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)*, 2016, pp. 1-7.

[7] B. Hu, X. Zhang, L. Fu, H. Li, Y. M. Abdullah, Y. Wang, Lurao Liu and Jin Wang, "Device loss comparison of GaN device based LLC, dual active bridge and phase shift quasi switched capacitor circuit", in *Energy Conversion Congress and Exposition (ECCE), 2016 IEEE*, 2016, pp. 1-7.

[8] J. Liu, J. Zhang, T. Q. Zheng and J. Yang, "A Modified Gain Model and the Corresponding Design Method for an LLC Resonant Converter", *IEEE Transactions on Power Electronics*, vol. 32, no. 9, pp. 6716 - 6727, Sep. 2017.

[9] C. Yeon, J. Kim, M. Park. I. Lee and G. Moon, "Improving the Light-Load Regulation Capability of LLC Series Resonant Converter Using Impedance Analysis", *IEEE Transactions on Power Electronics*, vol. 32, no. 9, pp. 7056 - 7067, Sep. 2017.

[10] G. Ivensky, A. Kats and S. Ben-Yaakov, "An RC load model of parallel and series-parallel resonant DC-DC converters with capacitive output filter," *IEEE Transactions on Power Electronics*, vol. 14, no. 3, pp. 515-521, May. 1999.

[11] K. Harada, A. Katsuki, M. Fujiwara, H. Nakajima and H. Matsushita, "Resonant converter controlled by variable capacitance devices," in *Proc. 21 Annual IEEE Conference on Power Electronics Specialists*, 1990, pp. 273-280.

[12] A. Katsuki, K. Shirouzu, K. Harada and M. Fujiwara, "Improved variable capacitance device and its applications to resonant converters," in *Proc. of Intelec 93: 15th International Telecommunications Energy Conference*, 1993, vol. 2, pp. 242-246.

[13] K. Harada; A. Katsuki; M. Fujiwara; H. Nakajima; H. Matsushita "Resonant converter controlled by variable capacitance devices," *IEEE Transactions on Power Electronics*, vol, 8, no. 4, pp. 404–410, 1993.

[14] A. Katsuki and T. Oki, "Leakage current suppression in the variable capacitance device for the use in AC power converters," in *Proc. IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS),* 2013, pp. 90-95.

[15] A. Katsuki and T. Oki, "Suppression of Leakage Current and Distortion in Variable Capacitance Devices and their Application to AC Power Regulators," Journal of power Electronics, vol. 16, no. 1, pp. 66-73, 2016

[16] Y. Hu, A. Amara, A. Ioinovici, **"**LLC resonant converter operated at constant switching frequency and controlled by means of a switched-capacitor circuit" in *1st International Future Energy Electronics Conference (IFEEC)*, 2013, pp. 691–696.

[17] R. L. Steigerwald, A. Ferraro and F. G. Turnbull, "Application of Power Transistors to Residential and Intermediate Rating Photovoltaic Array Power Conditioners," in IEEE Transactions on Industry Applications, vol. IA-19, no. 2, March 1983, pp. 254-267.