Proceedings of the 2nd Euro-Asian Pulsed Power Conference, Vilnius, Lithuania,September 22–26, 2008

Experimental Studies on Charging Operation of a Compact Repetitive Tesla Transformer

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Charging operations of a compact Tesla transformer were experimentally investigated, in single-shot and rep-rate (50 pps for 1 s) modes, respectively. The charging limitations were also explored. The experimental results were compared and analyzed. The maximum secondary charging voltages of the Tesla transformer were measured to be 380 kV and 300 kV in single-shot and rep-rate modes, respectively. The RMS pulse-to-pulse instability of the secondary charging voltage is generally less than 10% but increases with the increasing initial voltage across the primary capacitor. Since the secondary capacitor of the Tesla transformer is a pulse forming line (PFL), continued operation is possible if there is breakdown in the PFL. Furthermore, operation can even be continued under occasional breakdown for some pulses, without the effects on the operations of subsequent pulses.

PACS numbers: 84.30.Ng, 84.30.Jc, 84.30.Qi, 84.70.+p

1. Introduction

Development of high power microwave (HPM) devices requires pulsed power accelerators of small volume, compact structure and high rep-rate. Tesla transformers built in a coaxial PFL are extensively used in the field of pulsed power accelerators due to their compact structure, high coupling coefficient and high energy transferring efficiency. It is well known that SINUS accelerators [1–4], developed by the Institute of high Current Electronics (IHCE), Russia, hold a lead in pulsed power accelerators over the world. For certain special applications, it is important to use a pulsed power accelerator of small volume and compact structure with the capability of repetitive operation. The accelerator, in which the Tesla transformer is built into the PFL, is the key to this requirement. In this paper, charging operations of a Tesla transformer, particularly their limitations, are experimentally investigated. The experimental results were compared in single-shot and rep-rate modes.

2. Experimental setup

A compact Tesla transformer, shown in Fig. 1, consists of a primary winding, a secondary winding, and a magnetic core built in a coaxial PFL filled with capacitor oil. The magnetic core is made of thin electrical steel strip and forms the main part of the PFL's conductors. The primary capacitor arises from the capacitor C_1 of the primary energy source whereas the secondary capacitor C_2 is defined by the PFL geometry and permittivity of the oil within. The oil of PFL is pressurized up to 1.6 MPa, with electrical breakdown of the oil depending on oil pressure. Once the main thyristor S_{m} is on, the primary capacitor C_1 with the initial voltage U_0 will charge the PFL capacitor C_2 until the maximum voltage $U_{2\max}$ through the Tesla transformer. After the voltage U_{C1} across the primary capacitor remains the residual voltage $-U_{\mathrm{r}}$, the primary capacitor C_1 is recharged up to the initial voltage U_0 through the primary energy source. The voltage U_{C1}, across the capacitor C_1, and that across the PFL, U_{C2}, are respectively measured using capacitive and resistive dividers.

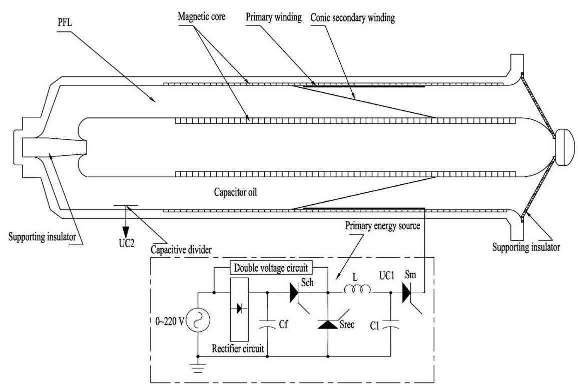

Fig. 1. A compact Tesla transformer built in a coaxial PFL.

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The geometrical and electrical parameters of the Tesla transformer are listed as follows: the length $l_{\mathrm{FL}} = 57.8$ cm, the inner diameter $2r_1 = 7.4$ cm, the outer diameter $2r_2 = 15.6$ cm, the primary inductance $L_1 = 730$ nH, the secondary inductance $L_2 = 576$ mH, the coupling coefficient $k = 0.957$, the ratio of the squared resonant frequencies between the secondary and primary circuits $\alpha = 1.6$, the primary capacitance $C_1 = 120$ μF, the secondary capacitance $C_2 = 110$ pF, the maximum PFL charging time $t_z = 7$ μs, and the energy transferring efficiency $\eta = 50\%$.

3. Experiment on charging operation

Charging operation of the Tesla transformer is carried out for the different initial voltages U_0 across the primary capacitor in a single-shot mode. The waveforms of the primary and secondary voltages, denoted by U_{C1} and U_{C2}, respectively, are both monitored. Figure 2a shows the measured waveforms and corresponding ones calculated by the approximate solution formula [4]. It

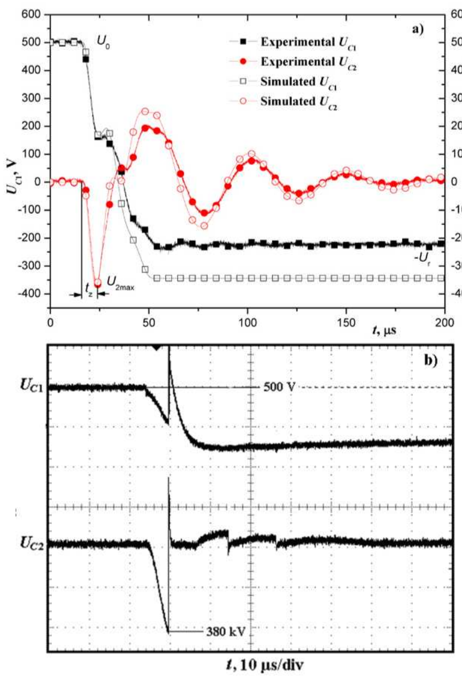

Fig. 2. Waveforms of primary and secondary voltages of the Tesla transformer in single-shot mode: (a) without breakdown and (b) with breakdown.

indicates that the measured and calculated voltage waveforms are in agreement with each other. Moreover, the voltage ratio n_{v} of the Tesla transformer is about 800. Once the maximum secondary charging voltage $U_{2\max}$ exceeds its critical value, the PFL breakdown will occur. The voltage waveforms, corresponding to the breakdown condition, are shown in Fig. 2b. The maximum PFL charging voltage $U_{2\max}$ is obtained to be 380 kV. Therefore, the maximum electric field strength of PFL is calculated to be $E_{\max} = U_{2\max}/[r_1 \ln(r_2/r_1)] = 138$ kV/cm, a little lower than the breakdown electric field strength $E_{bd} = 300 t_{\mathrm{e}}^{-1/3} A^{-1/10} = 170$ kV/cm calculated by the well-known Martin formula [5]. The decrease in the experimental breakdown strength may be explained by the PFL's high surface roughness [6] or the unoptimized PFL structure. Experiment also shows that the system can recover following breakdown of the PFL. That is, the charging operation can continue after PFL breakdown occurs provided the voltage of the next PFL pulse does not exceed the experimental breakdown value.

Charging operation in rep-rate mode at 50 pps for 1 s is carried out. The quantity of heat produced can be endured by the Tesla transformer, so that a cooling system can be unadopted. The primary and secondary voltage waveforms in this mode are shown in Fig. 3a. One can see

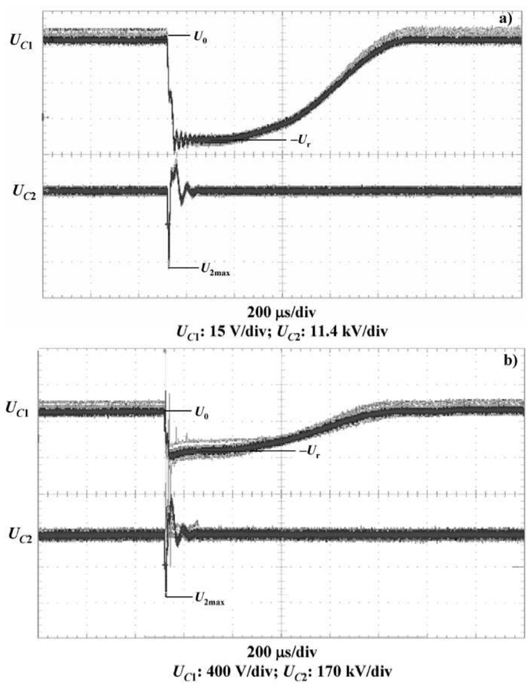

Fig. 3. Waveforms of the primary and secondary voltages of the Tesla transformer at 50 pps for 1 s in the cases of (a) PFL charging operation and (b) PFL breakdown for a few pulses.

that the repetitive operation is steady. In addition, the primary and secondary voltage waveforms are the same as in single-shot mode. Once the maximum secondary charging voltage for the first pulse in a batch exceeds its critical value, PFL breakdown will occur. The primary and secondary voltage waveforms corresponding to this situation are shown in Fig. 3b. The average value of the maximum PFL charging voltage is obtained to be 300 kV. Therefore, the maximum PFL electric field strength in repetitive mode with 50 pps for 1 s is $E_{\max} = 110$ kV/cm. It decreases 15% compared with that in a single-shot mode. In rep-rate mode, the maximum PFL electric field strength is less because the PFL is subjected to a high electric field for a prolonged time and the charging voltages, for the initial several pulses, are higher than the 300 kV critical value. Moreover, the repetitive charging operation may be continued if PFL breakdown occurs for only a few pulses in a batch. In other words, the PFL breakdown can be recovered under occasional breakdown for some pulses, without the effects on the charging operations of subsequent pulses.

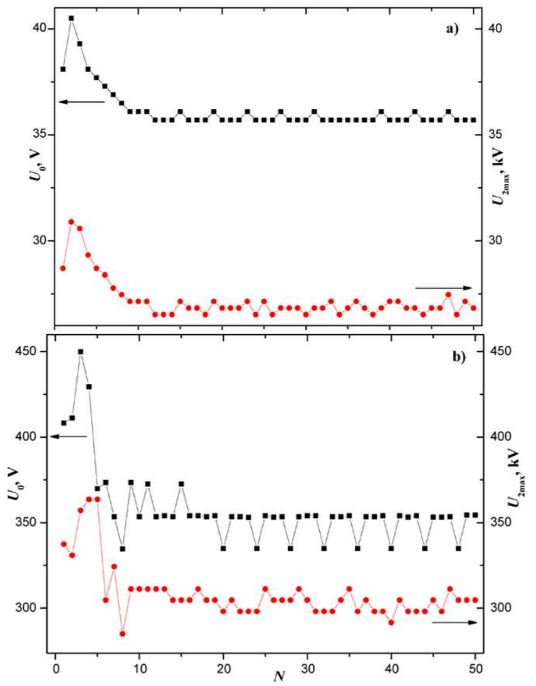

Fig. 4. Maximum primary and secondary voltages versus sequence number in a batch of pulses at 50 pps: (a) without breakdown and (b) with breakdown for a few pulses.

Figures 4a and 4b show the dependence of the initial voltage U_0 and the maximum PFL charging voltage $U_{2\max}$ on the sequence number N in a batch of pulses at 50 pps for 1 s without breakdown and with breakdown, respectively. The charging operation reaches the steady state through the adjustment of the first 10 pulses or so. Moreover, the average value of the maximum PFL charging voltage is a little lower than that in single-shot mode. Additionally, the RMS pulse-to-pulse instabilities of the primary and secondary voltages increase with the increasing initial voltage U_0 but are generally less than 10%.

4. Conclusions

In summary, the compact Tesla transformer can operate steadily in single-shot and rep-rate modes. Meanwhile, the maximum secondary charging voltages are 380 kV and 300 kV in single-shot and rep-rate (50 pps for 1 s) modes, respectively. Moreover, the charging operation can be continued under occasional PFL breakdown for some pulses, without the effects on the charging operations of subsequent pulses.

References

[1] G.A. Mesyats, S.D. Korovin, A.V. Gunin, V.P. Gubanov, A.S. Stepchenko, D.M. Grishin, V.F. Landl, P.I. Alekseenko, *Laser and Particle Beams* **21**, 197 (2003).

[2] S.D. Korovin, V.V. Rostov, *Russian Physics Journal* **39**, 21 (1996).

[3] V.P. Gubanov, S.D. Korovin, I.V. Pegel, A.M. Roitman, V.V. Rostov, A.S. Stepchenko, *IEEE Transactions on Plasma Science* **25**, 258 (1997).

[4] S.D. Korovin, Tomsk: Institute of High Current Electronics (IHCE), Siberian Division (SD), Russian Academy of Sciences (RAS), Preprint Technical Report 47, 1988 (in Russian).

[5] J.C. Martin, *Proceedings of the IEEE* **80**, 934 (1992).

[6] Z. Zhang, J. Zhang, J. Yang, *Plasma Science and Technology* **7**, 3161 (2005).