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A high-voltage pulse transformer with a modular ferrite core

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A high ratio (winding ratio of 1:80) pulse transformer with a modular ferrite core was developed for a repetitive resonant charging system. The magnetic core is constructed from 68 small blocks of ferrites, glued together by epoxy resin. This allows a high degree of freedom in choosing core shape and size. Critical issues related to this modular design are the size tolerance of the individual ferrite blocks, the unavoidable air gap between the blocks, and the saturation of the core. To evaluate the swing of the flux density inside the core during the charging process, an equivalent circuit model was introduced. It was found that when a transformer is used in a resonant charging circuit, the minimal required volume of the magnetic material to keep the core unsaturated depends on the coupling coefficient of the transformer and is independent of the number of turns of the primary winding. Along the flux path, 17 small air gaps are present due to the inevitable joints between the ferrite blocks. The total air gap distance is about 0.67 mm. The primary and secondary windings have 16 turns and 1280 turns, respectively, and the actually obtained ratio is about 1:75.4. A coupling coefficient of 99.6% was obtained. Experimental results are in good agreement with the model, and the modular ferrite core works well. Using this transformer, the high-voltage capacitors can be charged up to more than 70 kV from a low-voltage capacitor with an initial charging voltage of about 965 V. With 26.9 J energy transfer, the increased flux density inside the core was about 0.23 T, and the core remains unsaturated. The energy transfer efficiency from the primary to the secondary was around 92%. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2830943]

I. INTRODUCTION

Transformers are often used in pulsed power systems to resonantly step up the charging voltage. It can be either an air core transformer or a magnetic core transformer. For an air core transformer, there is no saturation problem, and it is lightweight and easy to construct. However, the coupling coefficient k is low (normally k is less than 0.8).[1,2] To obtain an efficient energy transfer, the air core transformer is normally used in dual resonant mode, i.e., as a Tesla transformer.[3] And at least one primary oscillation cycle is needed to accomplish the charging process (when $k=0.6$).[4] Moreover, the charging voltage is bipolar, which makes it difficult to use semiconductor switches [thyristor, insulated gate bipolar transistor (IGBT), and metal-oxide-semiconductor field effect transistor (MOSFET)] or magnetic switches. When a magnetic core is used, a high coupling coefficient ($k>0.99$) can be obtained.[5,6] By using the magnetic transformer in a resonant charging circuit, an efficient energy transfer can be accomplished within only half a primary oscillation cycle, i.e., in single resonant mode.

One critical issue associated with a magnetic core transformer is the saturation of the core. Though the coupling coefficient of a magnetic core transformer is high, it is always less than 1. In a resonant charging circuit, the unavoidable leakage inductance of the transformer affects the charging time and thus also affects the flux density in the core. The influence of the coupling coefficient k on the flux density in the core has never been reported in literature. In this paper, an equivalent circuit model is introduced to analyze the effect of the coupling coefficient k on the swing of the flux density in the core of a transformer during one charging cycle. Based on this model, a high ratio (winding ratio of 1:80) magnetic transformer was developed. Ferrite blocks were adopted to make the core. Totally 68 small blocks were used and glued together by epoxy resin. Along the magnetic path of the core, 17 small air gaps are present due to the inevitable joints between the blocks. The transformer was successfully applied in a repetitive resonant charging system. It was found that the modular ferrite core works well and that the transformer meets the design requirements. Detailed information about the effect of the coupling coefficient k, the design of the transformer, and the experimental results will be presented.

II. EFFECT OF THE COUPLING COEFFICIENT K ON THE CORE VOLUME

Figure 1 shows the resonant charging circuit and its equivalent circuits. The resonant circuit, as shown in Fig.

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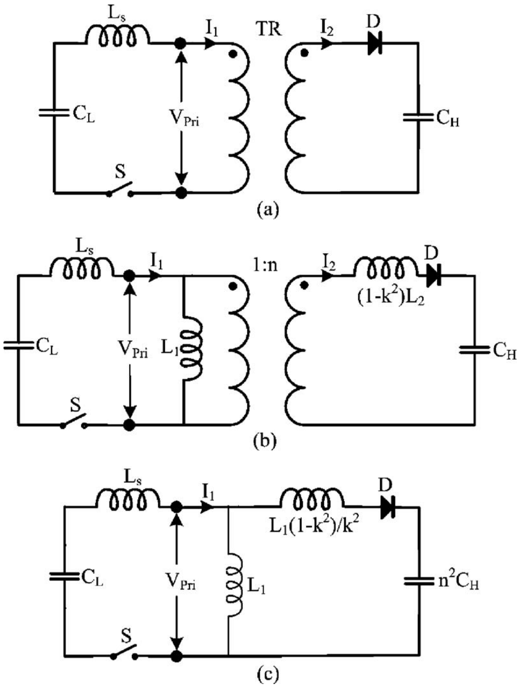

FIG. 1. (a) the resonant charging circuit; (b) the transformer is represented by an ideal transformer combined with two uncoupled inductors; (c) the simplified equivalent circuit, where the components at the secondary side are transferred to the primary side.

1(a), includes a low-voltage capacitor C_L, a stray inductor L_s (introduced by the connection leads), a transformer TR, a switch S, a diode D, and a high voltage capacitor C_H. The transformer TR can be represented by an ideal transformer in combination with two uncoupled inductors,[7] as shown in Fig. 1(b), where L_1 and L_2 are the primary and secondary inductances of the transformer TR, respectively. k is the coupling coefficient of the transformer TR and is equal to $M/\sqrt{L_1L_2}$ (M is the mutual inductance of the transformer), and n is the ratio of the transformer and is equal to M/L_1 or $k\sqrt{L_2/L_1}$. By transferring the inductance $(1-k^2)L_2$ and capacitor C_H to the primary side of the transformer TR, one may derive the equivalent circuit shown in Fig. 1(c).

When the coupling coefficient k is large enough, L_1 will be significantly larger than the inductance $L_1(1-k^2)/k^2$. And thus most of the energy from C_L will be transferred into n^2C_H and only a small part will be absorbed by L_1 during one charging cycle. Ignoring L_1 and energy losses during the charging cycle, one can derive the following expressions for the situation that $C_L=n^2C_H$ according to the model shown in Fig. 1(c).

$$V_{\mathrm{Pri}}(t)=\frac{V_0}{2}\left(1+\frac{L-L_s}{L+L_s}\cos\omega t\right),\quad 0\leqslant\omega t\leqslant\pi, \tag{1}$$

$$\Delta T=\pi\sqrt{(L_s+L)C}, \tag{2}$$

$$\Delta B=\frac{1}{AN_1}\int_0^{\Delta T}V_{\mathrm{Pri}}(t)dt=\frac{\pi V_L\sqrt{CL_1}}{2N_1A}\sqrt{\frac{L_s}{L_1}+\left(\frac{1}{k^2}-1\right)}. \tag{3}$$

In the above equations, $V_{\mathrm{Pri}}(t)$, V_0, ΔT, and ΔB are the voltage at the primary side of the transformer, the initial voltage on C_L, the charging time, and the incremental flux density inside the core, respectively. L is the leakage inductance of TR and is equal to $L_1(1-k^2)/k^2$, and $C=C_L/2$. A and N_1 are the cross section of the core and the number of turns of the primary winding, respectively. The inductance of the primary winding can be approximated as

$$L_1=\frac{N_1^2\mu A}{\ell}. \tag{4}$$

In Eq. (4), μ and ℓ are the permeability of the core and the mean length of the magnetic path, respectively. Substituting Eq. (4) into Eq. (3), one may derive the relationship between ΔB and the volume of the core $[A\ell]$.

$$\Delta B=\frac{\pi}{2}\sqrt{\frac{\mu E}{A\ell}}\sqrt{\frac{L_s}{L_1}+\left(\frac{1}{k^2}-1\right)}, \tag{5}$$

where E is the energy transferred per pulse and equal to CV_0^2. From Eq. (5), it can be seen that ΔB is a function of the energy transferred per pulse E, the volume of the core $[A\ell]$, the ratio of L_s to L_1, and the coupling coefficient k.

For proper operation, ΔB must be less than the allowable swing of the flux density ΔB_m of the applied magnetic material. And therefore the volume of the core must be designed according to the following condition:

$$[A\ell]\geqslant\frac{\pi^2\mu E}{4\Delta B_m^2}\left[\frac{L_s}{L_1}+\left(\frac{1}{k^2}-1\right)\right]>\frac{\pi^2\mu E}{4\Delta B_m^2}\left(\frac{1}{k^2}-1\right)$$
$$=[A\ell]_{\mathrm{critical}}. \tag{6}$$

From the above equation, one can see that the volume of the core must be larger than a critical volume $[A\ell]_{\mathrm{critical}}$, which is determined by the coupling coefficient k.

It is noted that the calculated values for ΔT and ΔB on the basis of the model described above are a little larger than the actual values. The higher the coupling coefficient k, the less the difference becomes. Especially when $k>99\%$, the differences for ΔT and ΔB are less than 0.5% and 1.4% respectively.

III. DESIGN AND CONSTRUCTION

The transformer is designed for a resonant charging system[8] to charge the high-voltage capacitor C_H (about 10 nF) to a voltage of 70 kV, where the low-voltage capacitor C_L is initially charged to about 1 kV. Thus the voltage transfer ratio of the transfer needs to be at least 1:70; actually the winding ratio was chosen to be 1:80. Ferrite blocks were used to construct the core. With regard to the ferrite material, the relative permeability, the saturation flux density, and the residual flux density are 2400, 0.5 T, and 0.15 T, respectively. The dimensions of each ferrite block are $5\times5\times10$ cm^3. The ferrite blocks are glued together by epoxy resin to obtain the desired core shape and dimensions. The advantage of using discrete ferrite blocks is the flexibility in construction of various kinds of cores (C type or shell type) with various dimensions.

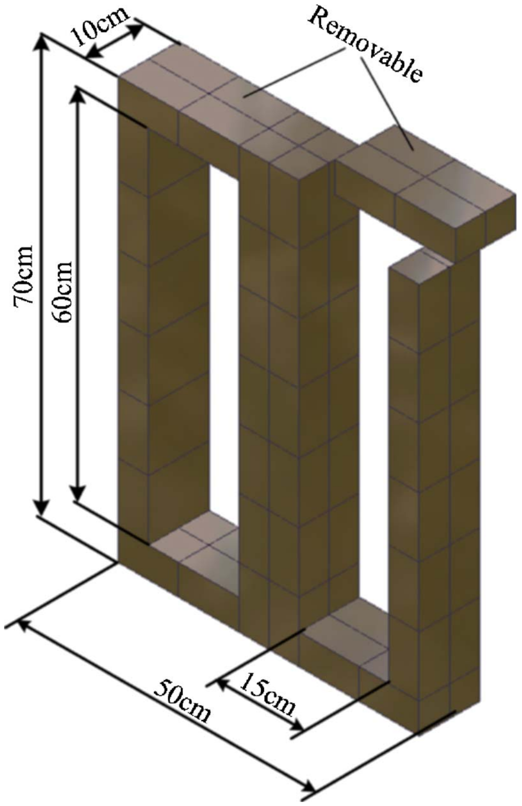

FIG. 2. (Color online) Transformer core.

A. Determine the volume of the core

To estimate the critical volume of the ferrite core according to Eq. (6), some assumptions were made: (i) The stray capacitance of the transformer is assumed to be around 0.5 nF and is added to the high voltage capacitor C_H. So C_H becomes 10.5 nF; thus under the matching condition $C_L=n^2C_H$, the transferred energy per pulse E is about 33 J at $V_0=1$ kV. (ii) According to the specification of the used ferrite material, the allowable swing of the flux density is 0.35 T; in this design, a value of $\Delta B_m=0.3$ T was used. (iii) The coupling coefficient k and the relative permeability μ_r of the core were empirically determined to be 0.996 and 1200, respectively. Under these assumptions, from Eq. (6), the critical volume of the core was estimated to be 11 190 cm^3, which means that at least 45 ferrite blocks are needed. Due to the stray inductance and to ensure the proper operation of the transformer 68 ferrite blocks were actually used. By gluing these blocks together with epoxy resin, a shell-type core was made, as shown in Fig. 2. The size of the core is $50\times 10\times 70$ cm^3; other dimensions are shown in Fig. 2. Except for the two removable blocks on the top, all blocks are glued together. The mean length of the magnetic path is 1.7 m. Along the magnetic path, 17 air gaps are present due to the inevitable joints between the blocks. The initially predicted total length of the 17 gaps is between 0.5 and 1 mm.

B. Select the number of turns of the primary winding

The number of turns of the primary winding N_1 was chosen according to the specification of the resonant charging system. To keep the charging system within the safe region, the maximum primary current must be less than the current rating $(2kA)$ of the thyristor switch used in the resonant charging system. Based on the model shown in Fig. 1(c), with the assumptions of $k=0.996$ and $L_s=0$ the peak primary current was estimated for different turn numbers from 10 to 20. These estimations were made for two different total lengths of air gaps, i.e., 1 and 0.5 mm, respectively. The primary turn number $N_1=16$ was chosen, since for this value the primary peak current will stay within safe margins. In addition, other parameters, e.g., the equivalent μ_r, primary inductance L_1, etc., were evaluated when $N_1=16$, as shown in Table I. The transformer will operate properly with $N_1=16$, provided that the total length of air gaps could be controlled between 0.5 and 1 mm.

TABLE I. Evaluation of the design when $N_1=16$.

	The total distance of gaps	
K=99.6%	1 mm	0.5 mm
Equivalent μ_i	995.4	1407
Primary inductance L_1	1.88 mH	2.66 mH
Leakage inductance L	15.15 μH	21.42 μH
Charging time ΔT	70.9 μs	84.3 μs
Incremental density ΔB	0.22 T	0.26 T
Peak primary current	1.49 kA	1.25 kA

C. Construction

The 16-turn primary winding was made from copper foil with a thickness of 1 mm and a width of 29 mm. The windings are wound on a square bobbin made from fiberglass. The secondary winding has a turn number of 1280 and is wound on a cone-shaped fiberglass bobbin. It was made from copper wire with a diameter of 0.42 mm. To reduce the winding resistance, two parallel layers were used. They were interconnected at the middle (i.e., the top layer goes to the bottom and the bottom layer goes to the top). Both the primary and the secondary are placed around the middle leg of the core. An aluminum cylindrical screen with a 1 cm split was positioned between the primary and secondary windings, in order to prevent the capacitive coupling between the primary and the secondary. The secondary winding is equipped with a round ring to control the high electric field. The two outer legs of the core are also provided with field-control aluminum parts. The whole transformer is supported by a wooden frame. A photo of the transformer is shown in Fig. 3. This transformer is immersed into transformer oil. The measured parameters are shown in Table II. According to the primary inductance, the effective values for μ_r and the total length of the air gaps are estimated to be 1238 and 0.665 mm, respectively. These values are within the estimated ranges shown in Table I. A coupling coefficient of 99.62% was obtained, and the actual ratio n is about 1:75.4.

IV. EXPERIMENTAL RESULTS ON A RESONANT CHARGING SYSTEM

The designed transformer (TR) was applied within a setup as shown in Fig. 4. It consists of a resonant charging

FIG. 3. (Color online) Photo of the transformer.

unit[8] and a high-voltage pulser. The high-voltage pulser includes a high-voltage capacitor C_H, a switch S, an *LCR* trigger circuit, and a resistive load (about 82 Ω). The switch S is a multiple-gap spark gap switch[9] consisting of three 9 mm gaps. The LCR trigger circuit[10] consists of an inductor *L*, a capacitor *C*, and a resistor *R*. Detailed information about the mechanism of the *LCR* trigger circuit was reported previously.[10] The value of the high-voltage capacitor C_H is 10.37 nF.

The principle of the resonant charging system was comprehensively discussed previously.[8] Initially, the storage capacitor C_0 is charged up to V_0 (~535 V). The system accomplishes one charging cycle in three steps. First, by closing thyristor Th_1, the capacitor C_L is charged to about 1 kV by the storage capacitor C_0. Second, after the charging of C_L is finished and thyristor Th_1 is switched off, by closing thyristor Th_2 the capacitor C_H is charged by C_L via the transformer TR. Then, after the charging of C_H is finished and thyristor Th_2 is switched off, C_H is discharged into the load via the spark gap switch S. Finally with thyristor Th_3 the polarity of the remaining voltage on C_L can be reversed before the next charging cycle.

Figure 5 shows typical voltages on the capacitors C_L and C_H, respectively during one charging cycle when $C_L=60.6\ \mu\mathrm{F}$, and $C_H=10.37$ nF. The low-voltage capacitor C_L was charged up to 965 V from an initial voltage of 16 V. After closing thyristor Th_2, the voltage on C_L dropped to 16 V again, and the high-voltage capacitor C_H was charged up to 70.3 kV within a charging time of 79 μs, which implies that the designed transformer meets the voltage requirement.

TABLE II. Measured parameters of the transformer.

Primary inductance L_1	2.34 mH
Secondary inductance L_2	13.46 H
Coupling coefficient k	99.62%
Actual ratio n	75.4
Primary winding resistance R_P	9.63 m Ω
Secondary winding resistance R_S	80.35 Ω
Primary stray capacitance C_P	2.4 nF
Secondary stray capacitance C_S	680 pF

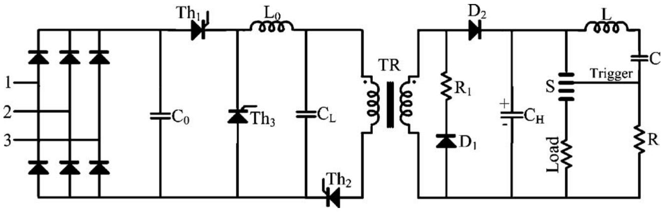

FIG. 4. The schematic diagram of the experimental setup.

Figure 6 shows the typical voltage and current on the primary winding of the transformer when $C_L=60.6\ \mu\mathrm{F}$ and $C_H=10.37$ nF. It can be seen that the peak value of the primary current is 1.14 kA. This is about 57% of the current rating $(2kA)$ of thyristor Th_2, which indicates that the design of the transformer ensured the switch to be used safely. Furthermore, according to the current waveform shown in Fig. 6, the charging time is about 79 μs. The leakage inductance of the transformer $L_1(1-k^2)/k^2$ is about 17.8 μH, and the stray inductance L_S of the present system is approximately 2.9 μH. By integrating the primary voltage shown in Fig. 6, the swing of the flux density inside the core can be estimated. The result is shown in Fig. 7. It can be found, that when the charging is finished, the increased flux density inside the core is 0.23 T, which means that no saturation will occur for the present design of the transformer when the charging is complete. This value is in good agreement with the theoretical value of 0.232 T given by Eq. (5). The further increase of the flux density after the charging has been finished is caused by the voltage oscillation between the primary and the secondary (as shown in Fig. 6).

The total energy conversion efficiency η of the transformer was evaluated by the following equation:

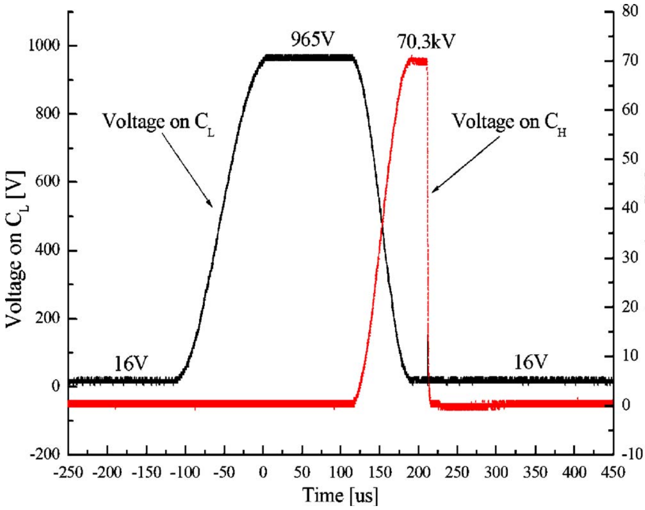

FIG. 5. (Color online) Typical voltages on C_L and C_H during one charging cycle when $C_L=60.6\ \mu\mathrm{F}$ and $C_H=10.37$ nF.

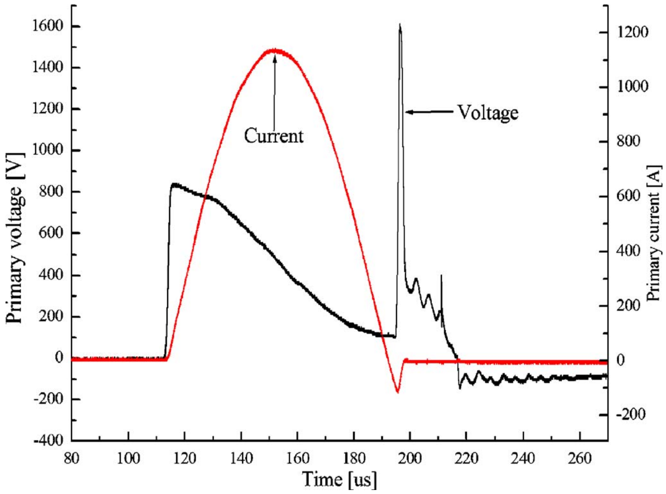

FIG. 6. (Color online) The typical voltage and current on the primary of the transformer when C_L=60.6 μF and C_H=10.37 nF.

$$\eta = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{\int V_H(t) I_H(t) dt}{\int V_{\text{Pri}}(t) I_{\text{Pri}}(t) dt}, \tag{7}$$

where E_{in} and E_{out} refer to the energy input into the transformer and the energy output from the transformer, namely, the energy flowed out from the diode D_2. $V_{\text{Pri}}(t)$, $V_H(t)$, $I_{\text{Pri}}(t)$, and $I_H(t)$ refer to the voltage across the primary of the transformer, the voltage on C_H, the current in the primary of the transformer, and the current at the secondary of the transformer, respectively. These four parameters were measured simultaneously when C_L=60.6 μF. The calculated values of E_{in} and E_{out} are given in Fig. 8. When the charging finished, the values of E_{in} and E_{out} are 26.9 and 24.7 J, respectively; thus the energy efficiency is 91.8%. The losses are mainly caused by the resistance of the primary and secondary windings, the secondary stray capacitance, and the transformer core (magnetizing energy E_M and eddy currents). The losses caused by them were estimated to be about 1.9%, 2.4%, 2.1%, and 1.8% respectively.

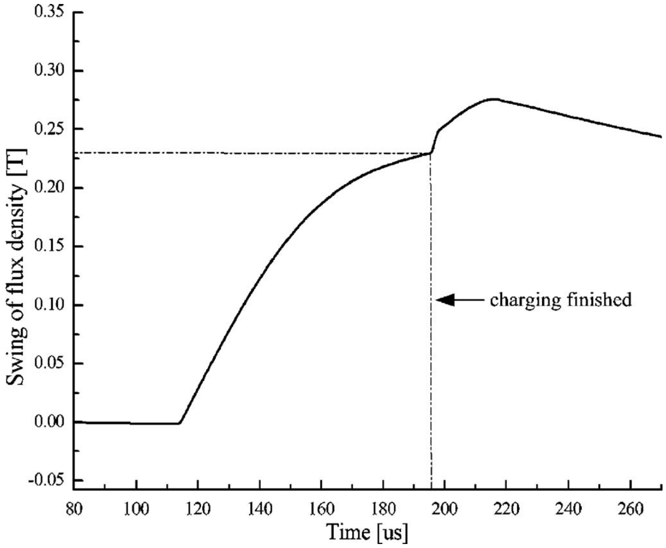

FIG. 7. The swing of the flux density ΔB inside the core when C_L=60.6 μF and C_H=10.37 nF.

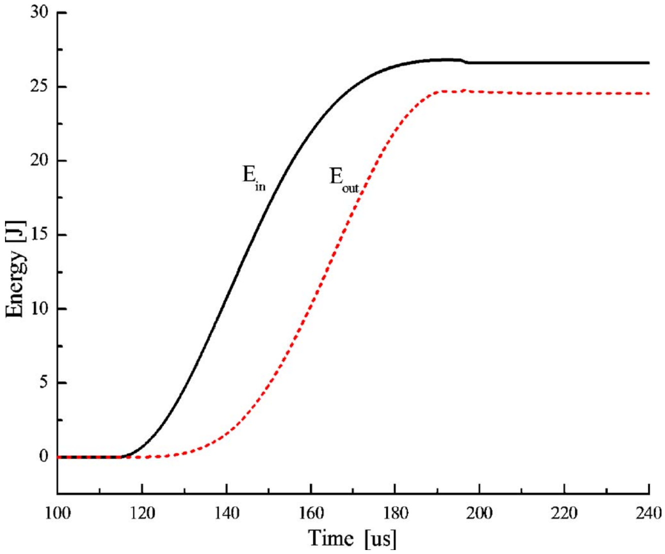

FIG. 8. (Color online) The values of E_{in} and E_{out} when C_L=60.6 μF and C_H=10.37 nF.

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