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Note: Compact high voltage pulse transformer made using a capacitor bank assembled in the shape of primary

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The experimental results of an air-core pulse transformer are presented, which is very compact ($<$10 Kg in weight) and is primed by a capacitor bank that is fabricated in such a way that the capacitor bank with its switch takes the shape of single-turn rectangular shaped primary of the transformer. A high voltage capacitor assembly (pulse-forming-line capacitor, PFL) of 5.1 nF is connected with the secondary of transformer. The transformer output voltage is 160 kV in its second peak appearing in less than 2 μS from the beginning of the capacitor discharge. The primary capacitor bank can be charged up to a maximum of 18 kV, with the voltage delivery of 360 kV in similar capacitive loads. © *2011 American Institute of Physics*. [doi:10.1063/1.3648119]

Some of the radiation sources, which require pulsed accelerators as their driver, operate with energies of the order of hundreds of joules, whereas the power requirement for their operation is in gigawatts. These pulsed accelerators have unique characteristic of very high-power delivery capability. The main components of such accelerators are energy-storage components and voltage-amplifiers operating in the order of 100 s of kilovolts to few megavolts. These voltage-amplifiers may be either a Marx generator or any Tesla/Pulse/Linear transformer. The major factors deciding the size of such voltage-amplifiers are energy required by the radiation source and the voltage levels of operation of the radiation source. In either of the above mentioned two cases of voltage amplifiers, the high voltage applied in the radiation source is provided by a capacitor which may be oil or water capacitor or erected capacitance of a Marx generator. From the application point of view, one needs compact energy-storage elements and compact voltage-amplifiers to drive such radiation sources.

As described above, the pulse voltage transformer is one of the schemes to uplift the voltages such that a pulse-forming-line capacitor (PFL) can be charged to the required high voltages. The pulse-forming-line is a capacitor assembly which can withstand the applied high voltages, desired for driving the matched loads requiring high electrical pulsed input power. It is very difficult to design or make compact pulsed transformer using magnetic cores because one has to struggle with the core saturation for attaining compactness in such high voltage transformer. Magnetic cores pose saturation limits depending upon their sizes. As the size is reduced the magnetic core gets saturated by relatively weaker magnetic field (and thereby from lesser energy density) and hence is difficult to be used. The another reason for not using the magnetic cores is that their presence makes the system slow by increasing the primary and secondary inductance values higher by a factor of permeability. It results in the high voltage overstressing for longer time scales of the system components around the transformer including the insulators or dielectrics and also makes them more prone to the voltage breakdown. Last, but not the least, reason of not using the magnetic cores is the cost and weight of the cores which may be significant in some cases. All above mentioned advantages of air-core far-overweigh the only serious disadvantage associated with it, i.e., the poor flux-coupling between the primary and the secondary of the transformer. However, to overcome this disadvantage, the use of Tesla transformer in double, triple resonance schemes is well reported.[1–7] Moreover, the other direction, in which people are working, to make compact pulse transformer is by using self-magnetic insulation technique.[8] As mentioned above, if the energy required is low and systems are operating very fast, i.e., in one or two microseconds, then the dielectric strength of all the circuit components is quite different to that of it, which would have been in the case when such systems were operated in few tens of microseconds. In moving the direction of making a compact and fast pulse transformer we are presenting an air-core pulse transformer which has its primary capacitor bank shaped in the form of single-turn winding. This reduces the flux losses in external circuit caused by the connections of capacitor bank to the primary of the transformer.

In Figure 1 we have shown the compact pulsed transformer which includes the primary capacitor bank as its single-turn primary. The primary capacitor bank is made by 20 cylindrical capacitors with axial leads; each of them is rated for 2.1 μF capacity and can be charged to a 4.5 kV maximum with a peak current delivery capacity of 15 kA. These capacitors require a modification on end-connection in order to make any low inductance discharge circuit. That is why the capacitors are arranged in such a way that the complete assembly takes the shape of one turn of primary of the pulse transformer which is rectangular in shape and contains four such sides. A parallel combination of five capacitors is used to make each of the four sides of rectangle shaped primary. The primary assembled in this way has the least inductance so that the capacitor bank delivers its energy to the high

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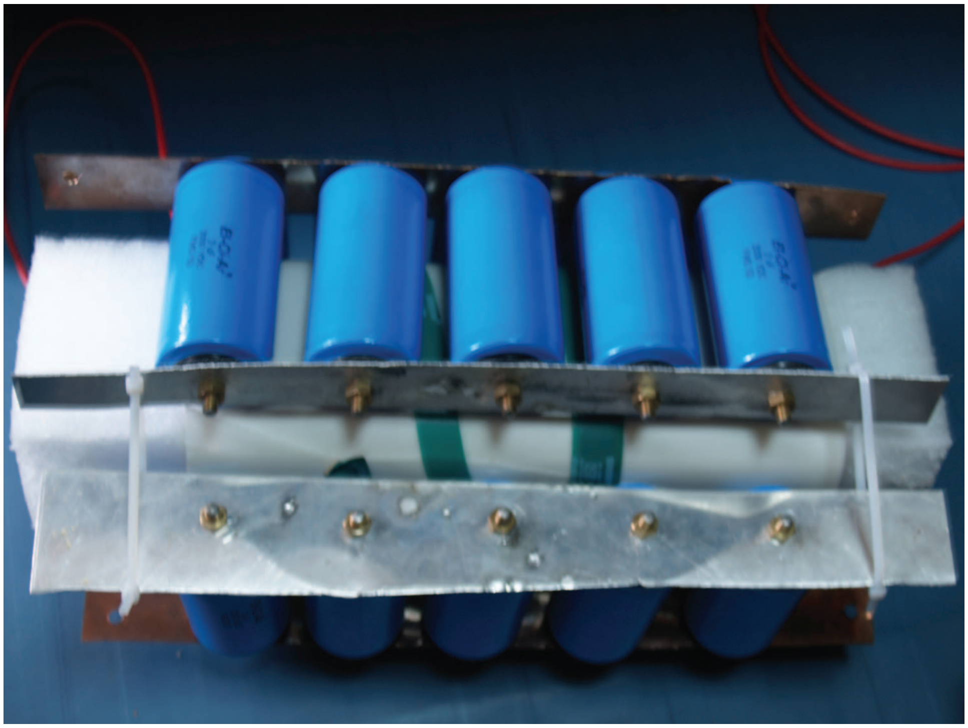

FIG. 1. (Color online) Compact pulse transformer using capacitor bank as its primary.

powers. The total capacitance of the primary capacitor bank is measured to be 2.46 μF and can be charged up to a maximum voltage of 18 kV. This transformer is nearly 35 cm in width. The distance between the ends of capacitor leads of each arm is 22 cm. The secondary of the transformer is made in the shape of helix, having 30 turns on 22 cm length, wound on the rectangular cross section former of 9 cm $\times$ 9 cm dimension. The secondary is placed inside the primary which has also has rectangular cross section (15 cm $\times$ 15 cm). The transformer is made with air-core in order to avoid magnetic saturation effects. The transformer is low in weight also. If required, it is easily possible to immerse the transformer in oil or in pressurized chamber for attaining higher voltages. The insulation between the primary and secondary is provided by rolling multiple layers of Mylar sheet around the secondary. The secondary capacitor (PFL) is made using 4 pieces of RG 218 cables each of 12 m. The total capacitance of the secondary PFL capacitor is 5.1 nF. The measured primary inductance (Lp) is 80 nH and secondary inductance (Ls) is measured to be 41 μH. The mutual inductance (M) between primary and secondary is measured to be 905 nH suggesting a value 0.5 for the achieved coupling coefficient (k). The ratio (LpCp/LsCs) of product of primary capacitance and primary inductance (LpCp) to the product of secondary capacitance and secondary inductance is 0.94 which is nearly equal to 1. It shows that under experimental constraints the Tesla machine is realized to a good extent using this pulse transformer design.

The power supply, for charging the primary capacitor bank, is made using a 230 V to 12 kV high-voltage step-up transformer. The output voltage of the high-voltage transformer is controlled by a variac connected in the input of the high-voltage transformer. The high-voltage transformer output is directly connected to the primary capacitor bank using a rectifier diode chain made of 30 numbers of 1 kV, 1 A diodes connected in series. By using the variac, the charging voltage of the capacitor bank can be adjusted. The switching of primary capacitor bank is done using a manual switch operated by inserting metal piece between two ends of primary capacitor bank. We have used a high bandwidth (25 MHz) high voltage probe having attenuation ratio of 10 000:1 for the measurement of secondary capacitor voltage.

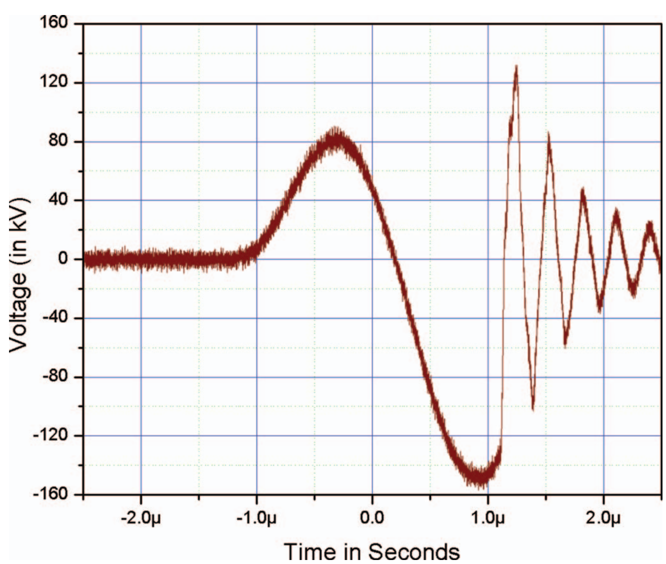

FIG. 2. (Color online) Voltage time history of PFL charged by the compact transformer.

In the Figure 2 we have presented the experimental results obtained from the pulse transformer reported in this paper. The secondary voltage of 160 kV at the PFL of 5.1 nF is achieved by the charging of primary capacitor bank at 8 kV only. The capacitor bank can be charged up to 18 kV (total primary energy 400 J) which will lead to 360 kV of secondary voltage at similar capacitive loads. Moreover, the charging of the PFL is done very fast which is within 2 μS from the beginning of the discharge in the primary capacitor bank. As far as energy efficiency of the system is concerned it is higher than 80% in the present configuration considering the second peak of secondary-voltage waveform. One more important thing observed in the achieved results is that the second peak in secondary is nearly twice of the first peak which is in opposite polarity and hence the control on the operation/switching of the output switch (after the PFL and connecting to load) is highly improved.

A compact pulse transformer is designed, developed, and tested for the voltage gains of 1:20 in the reported configuration of primary and secondary capacitances. It is characterized for 160 kV secondary voltage while working in unpressurized air. The transformer is made very compact and novel by using the capacitor bank assembly in shape of the single turn primary winding.

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