

## Design of Pulse Transformers for PFL Charging\*

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## Abstract

Air core pulse transformers powered by low voltage capacitor banks can be simple efficient systems for charging high-voltage (0.5 to 3 MV), pulse forming transmission lines (PFL) such as those used in electron and ion beam accelerators. In these applications pulse transformers must have the combined capability of high voltage endurance and high energy transfer efficiency, particularly in repetitive pulse systems where these features are of primary importance. The design of shielded, high-voltage, spiral, strip transformers which fulfill these requirements is described in this paper. Transformers of this type have been tested in three systems which operate with greater than 99 percent transfer efficiency and have not failed in over  $10^7$  shots.

## Introduction

High voltage pulse transformer charging systems typically consist of a low voltage capacitor bank coupled to a high voltage PFL through a voltage step up transformer as illustrated in Fig. 1. These systems have the advantage of not requiring an oil tank to insulate the primary storage capacitors and are generally more compact than Marx generators. With transformer systems, however, it can be difficult to achieve both high voltage endurance and high energy transfer efficiency. The reason for this is that operation at high voltages ( $> 500$  kV) necessarily requires that voltage grading devices be placed in high electric field regions where the magnetic fields are also high. Consequently, the magnetic fields line the voltage grading structures and often induce eddy current loops with opposing magnetic fields which partially cancel the fields in the main windings. This action produces a partial internal shorting of the transformer and significantly reduces the energy transfer efficiency of the system.

To avoid this shorting effect it is necessary to design voltage grading devices such that the magnetic field can diffuse through the assembly without inducing eddy currents. A grading structure that satisfies these requirements has been developed for spiral strip transformers which

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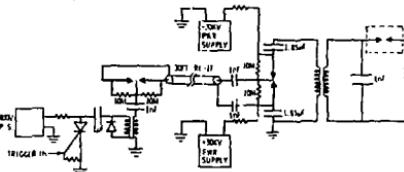


Fig. 1. Schematic of typical transformer charging circuit.

require electric field shaping across the margins of the secondary winding. It was found that a concentric ring cage, when properly assembled, was transparent to the magnetic field but maintained the proper electric field distribution in the margins. Figure 2 illustrates a typical ring cage assembly.

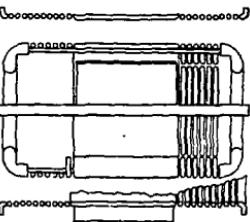


Fig. 2. Concentric ring cage assembly.

## Discussion

Spiral strip transformers are in general better suited to PFL charging applications than their helical wound counterparts because they have a higher power handling capacity and because they are less vulnerable to interturn breakdown from nanosecond transients fed back into the transformer secondary by the PFL discharges. The higher endurance of spiral strip windings to transient voltage breakdown is due to a more optimum capacitance distribution through the high <sup>1</sup> <sub>2</sub> <sup>3</sup> <sub>4</sub> <sup>5</sup> <sub>6</sub> <sup>7</sup> <sub>8</sub> <sup>9</sup> <sub>10</sub> <sup>11</sup> <sub>12</sub> <sup>13</sup> <sub>14</sub> <sup>15</sup> <sub>16</sub> <sup>17</sup> <sub>18</sub> <sup>19</sup> <sub>20</sub> <sup>21</sup> <sub>22</sub> <sup>23</sup> <sub>24</sub> <sup>25</sup> <sub>26</sub> <sup>27</sup> <sub>28</sub> <sup>29</sup> <sub>30</sub> <sup>31</sup> <sub>32</sub> <sup>33</sup> <sub>34</sub> <sup>35</sup> <sub>36</sub> <sup>37</sup> <sub>38</sub> <sup>39</sup> <sub>40</sub> <sup>41</sup> <sub>42</sub> <sup>43</sup> <sub>44</sub> <sup>45</sup> <sub>46</sub> <sup>47</sup> <sub>48</sub> <sup>49</sup> <sub>50</sub> <sup>51</sup> <sub>52</sub> <sup>53</sup> <sub>54</sub> <sup>55</sup> <sub>56</sub> <sup>57</sup> <sub>58</sub> <sup>59</sup> <sub>60</sub> <sup>61</sup> 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However, a simple spiral strip transformer, illustrated in Fig. 3, has the inherent weakness of arcing from the edges of the secondary winding strip from highly enhanced electric fields along the edges. Such breakdowns usually originate at the edge of one of the final secondary turns, flash across the margin and close the arc path to the primary or one of the lower voltage turns. The ensuing discharge typically ruptures the insulation sheets and leaves a heavy carbon deposit along the path of the arc.

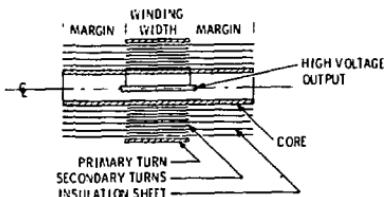


Fig. 3. Simple spiral strip transformer.

The high field enhancement along the edges of the winding is associated with the equipotential lines which emerge from between the turns and bend sharply around the edges toward the lower potential primary turn. The field enhancement in the edge regions limits the operation of a bare spiral strip to 300 to 400 kV even with the best insulating films and oils.

The edge breakdown problem can be eliminated by adding a coaxial shield across the margins of the secondary winding. The concentric shield constrains the electric field to a coaxial distribution across the margins which is nearly parallel to the uniform distribution through the thickness of the winding. Consequently, the field enhancement is greatly reduced and there is virtually no lateral field component to drive an arc across the margin.

The effectiveness of this shielding technique was demonstrated in an early transformer design shown in Fig. 4 which was tested to 1.25 MV without failure. The transformer had a single turn primary and a 1 inch thick, 30-turn, secondary winding. The shields were longitudinally slotted cylinders placed over the low voltage exterior and along the core. While this experiment clearly demonstrated that concentric shielding prevented edge breakdown, it was found that induced eddy currents in the shields as illustrated in Fig. 5 had a detrimental effect on the magnetic coupling. The open circuit gain which should have been near 30 was actually 12 and the energy transfer efficiency with a resistive load was approximately 25 percent.

#### Internal Shorting Experiments

The problem of internal transformer shorting was studied in two types of tests, inductance bridge measurements of a simulated primary turn with an



Fig. 4. Transformer with continuous concentric shields.

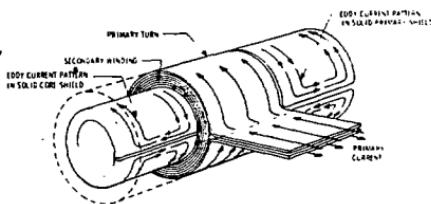


Fig. 5. Eddy currents in continuous cylindrical shields.

adjacent shield section and pulse discharge tests on a primary turn with various core configurations in the center. In both cases, shorting effects were observed as a decrease in circuit inductance from the unloaded primary turn inductance.

Figure 6 is a plot of inductance measurements on a 10 inch diameter, 6 inch wide primary turn with a 6 inch wide sleeve placed at different axial distances from one edge of the primary. The sleeve was intended to simulate a shield or structural component placed in some proximity to the magnetic field of the primary. In one case the sleeve was longitudinally slotted and in the other case it was continuous and acted as a shorted turn. The eddy current shorting effect for the slotted and shorted sleeve measurements was small but measurable as far as 4 inches away from the primary turn. With the axial spacing less than one inch, the effect was quite pronounced in both cases. With a one-half inch spacing, for example, the shorted sleeve produced a 13 percent change in the primary inductance and the open turn produced a 7.3 percent change.

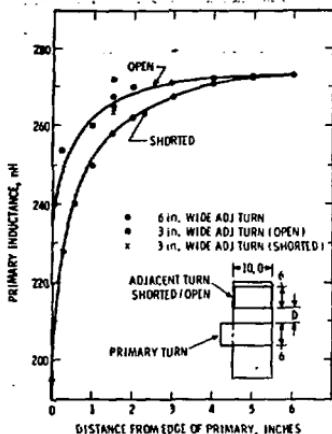


Fig. 6. Primary inductance variation with an adjacent shorted and open turn.

In the pulse discharge tests a  $14.5 \mu\text{F}$  capacitor was switched through a 4 inch diameter by 4 inch wide single turn primary coil. Circuit inductance was determined from the ringing frequency of the discharge. The unloaded inductance of the circuit (no core in the primary coil) was 98 mH. A slotted core tube of the same axial length as the primary produced no change in inductance but as the length of the slotted tube was increased to 8 inch, 12 inch and 14 inch the circuit inductance fell to 76 mH, 65 mH and 53 mH, respectively. This result indicated a shorting effect strongly dependent on shield length. Other shield configurations including screens, foils, longitudinal rods, etc. produced similar shorting effects. Only two types of shields showed virtually no shorting. One was a slotted cylinder of resistive film with a surface resistance of approximately 1000 ohms per square. The other was an array of rings interspaced approximately one eighth inch and longitudinally aligned with the axis of the primary turn. The rings were made with a gap in the hoop direction to prevent circumferential current flow and were connected together electrically along a single line opposite the line of gaps such that there were no closed loops that could conduct current in the assembly which linked the magnetic field. Pulse discharge tests on the resistive film and ring shield models showed a maximum of 3 percent inductance change with and without the shield assemblies in place.

Following these tests two prototype transformers were constructed, one with resistive film shields and one with a ring type core shield in combination with a continuous external shield which also served

as the primary turn. In testing the resistive film shielded transformer there were no measurable effects of internal shorting but the resistive film consistently broke down along the surface at voltages over 500 kV. Efforts to improve the film quality were unsuccessful. The ring core model with the continuous case was incorporated into an electrostatic beam generator (Fig. 7) and tested to 600 kV. In this application the transformer proved to have good high voltage endurance but with an energy transfer efficiency of 52 percent, it was still affected by eddy currents in the external shield. A third transformer (Fig. 8) was, therefore, constructed with ring shields on both the core and case. This transformer showed no measurable effects of internal shorting and was equal to the earlier model in high voltage endurance.

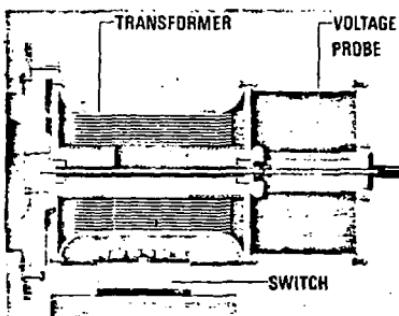


Fig. 7. Ring and cylinder shielded transformer.

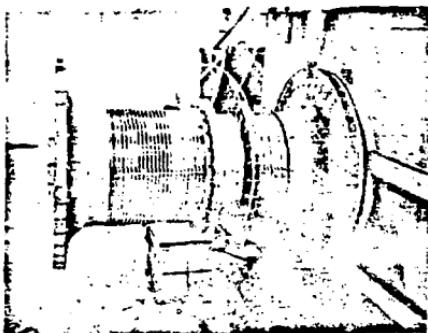


Fig. 8. Concentric ring shielded transformer.

### Operational Results

After initial testing, the concentric ring shielded transformer was incorporated into a repetitive impulse test facility and used for testing dielectric solids, liquids and composites.<sup>5</sup> In this application the transformer has been operated for greater than  $10^7$  shots in a voltage range between 500 kV and 1.5 MV at pulse rates from 1 to 200 pps. No winding failures or insulation flashovers have occurred throughout this service.

Two other ring shielded transformers have been built and operated in high voltage PFL charging systems. The essential features of both transformers are illustrated in Fig. 9. One is used in a 100 pps, 300 J electron beam generator<sup>3</sup> for charging a 1.2 nF PFL to 700 kV. It has operated for more than  $2 \times 10^7$  shots without failure. The second is incorporated in a 10 pps, 5 kJ high voltage pulser and charges a 4 nF water capacitor to 1.5 MV (Fig. 9). Prior to the repetitive pulse application, the transformer was successfully tested in a single shot mode to 3 MV.<sup>6</sup> Since the second repetitive pulse system has only recently been placed in service long term endurance data are not yet available for this transformer.

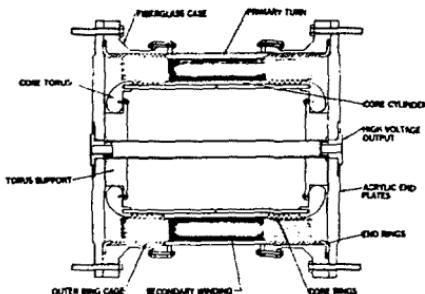


Fig. 9. PFL charging transformer.

All three ring shielded transformers have been operated in both single swing and dual resonance charging modes. With coupling coefficients ranging from 0.83 to 0.85, the energy transfer efficiency is typically around 60 percent in the single swing charge mode. In most cases, however, the transformers are operated in a dual resonance charging mode which requires matching the frequencies of the primary and secondary sections of the circuit and reducing the effective coupling coefficient to 0.6. This is accomplished with a transformer having a coupling coefficient greater than 0.6 by adding an appropriate amount of external inductance to the primary and secondary sections of the

circuit.<sup>6</sup> With the circuit properly tuned, energy transfer efficiencies are typically greater than 90 percent. It should be noted that the effects of eddy current shorting can not be compensated for by any means of external circuit tuning. The ring shielded transformers produced transfer efficiencies ranging from 91 percent for the 3 MV model to 94 percent for the 700 kV repetitive pulse model. These losses were divided in the approximate proportion of one percent in the transformer and five to eight percent in the spark gap switches and capacitors.

### Conclusions

Achieving high energy transfer efficiency in combination with high voltage endurance in an air core pulse transformer involves careful attention to the design of voltage grading devices and structural elements to avoid internal shorting. Concentric ring shielding of spiral strip type transformers has proven to be an effective technique for satisfying both requirements simultaneously. This design method has been scaled successfully from a few hundred kilovolts to 3 MV. There are no apparent reasons why even higher voltage transformers utilizing this technique could not be built. For the present, however, transformers operating up to a few megavolts have many useful applications in repetitive pulse accelerator systems where long shot life and high energy transfer efficiency are essential.

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