

# History of Soft Switching

## Part II

by Rudy Severns

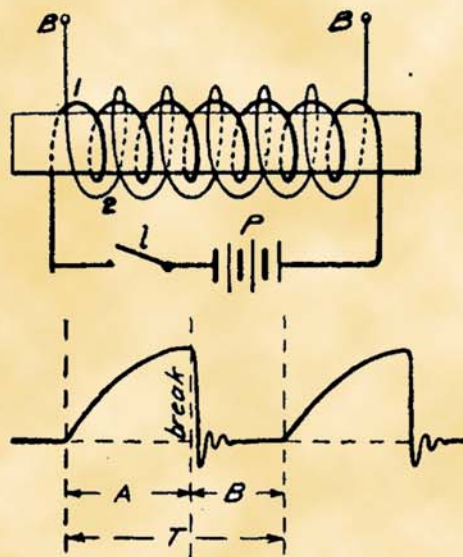


Figure 1. Basic induction coil

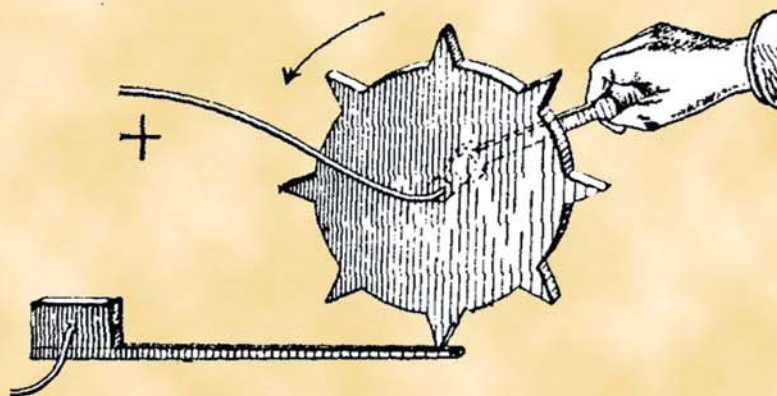


Figure 2. Page's spur-wheel breaker

### The Origin of The Capacitive Turn-Off Snubber

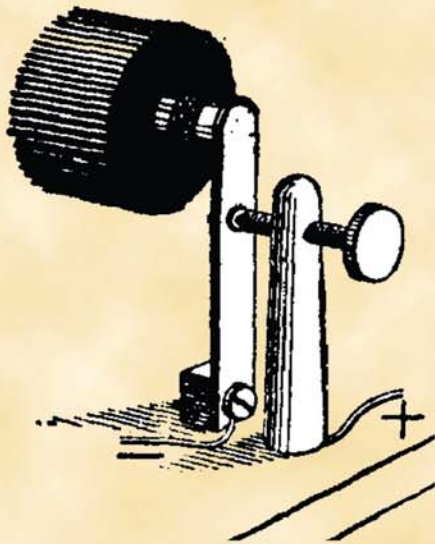
A point often overlooked is that in many soft-switching circuits the turn-off transition is controlled by nothing more than a very old-fashioned capacitive turn-off snubber. It is at turn-on where a number of ways to non-dissipatively discharge the capacitor have been devised. Soft switching really begins with the invention of the capacitive turn-off snubber. Very often the turn-off transition is referred to as a "zero-voltage" transition. This isn't really correct. It can be a low-voltage transition, but how low depends on the size of the snubber capacitor in proportion to the load current being switched. The turn-off losses can be greatly reduced but are not zero by any means. McMurray [1] has shown the relationship between capacitor value, load current and switch turn-off loss.

Very seldom can we clearly identify the originator of circuit ideas in widespread use over a long period of time. The capacitive turn-off snubber would surely seem to fall into that category. Not so! While poking through a couple of turn-of-the-century engineering

texts, [2,3] I found an unequivocal attribution for the origin of this snubber. In its day (1853), it was recognized as a pivotal invention that advanced the state of the art.

One of the key electrical discoveries of the 19th century was Faraday's invention of the transformer or induction coil. The induction coil was immediately adopted, and experimenters made rapid progress in improving it. Figure 1 shows an early circuit and associated waveforms. Note that this is basically a flyback converter!

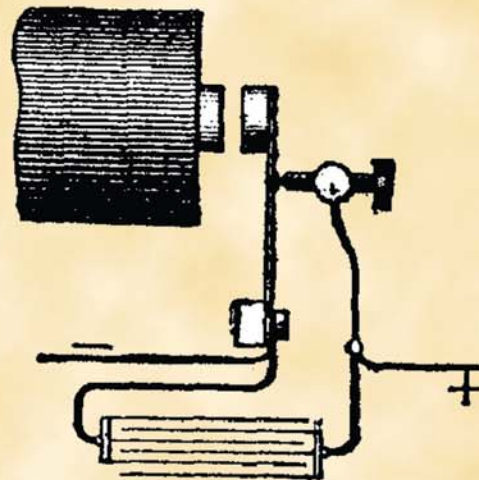
When operating from a DC source, it was recognized that nothing interesting happened until the primary circuit was closed and then opened quickly. If you wanted to do experiments, it was very helpful if you could open and close the primary circuit repetitively. Many schemes were advanced to accomplish this. One of the earliest (1836) is shown in figure 2. A spur-wheel with a hand crank provided the repetitive switching action. While the hand crank approach would work, it required someone to crank during the experiments and it was difficult to maintain a constant rotation speed.



*Figure 3. Neef's hammer interrupter*

An easier way, invented by Callan (1836) and improved by Neef (1840), is shown in figure 3. The idea is that the breaker contacts were on a leaf spring with an iron disk at one end. The disk was located close to the end of the core so that as the current built up in the primary winding, a point would be reached where the iron disk would be pulled over to the core, opening the contact, and breaking the primary circuit.

After a period of time, the energy in the core would dissipate reducing the force on the iron disk, and allowing the spring to reclose the contacts to repeat the cycle. The circuit is self oscillating and represents a very early version of a self-oscillating DC-AC inverter operating in the continuous conduction mode (the coil current did not quite go to zero before the spring closed the primary circuit for the next cycle). It is also an example of peak current-mode control of the switch because the switch opens when an appropriate peak current is achieved. Spring tension and spacing from the core were used to adjust the activation point.



*Figure 4. Fizeau's condenser around break*

As soon as the early workers had repetitive switching they immediately discovered the problem of opening a switch with an inductive load—there are switching losses. In the early days, the figure of merit for induction coils was the length of spark one could achieve on the secondary. Early on it was noticed that there was an arc across the primary switch when it opened. This arc had two effects. First, it rapidly eroded the contacts even when liquid mercury was used for one side of the switch. And secondly, the faster the primary switch arc was extinguished the longer the spark on the secondary.

It was recognized that the primary arc was reducing  $dI/dt$  and consuming energy which was not available for the secondary spark. In some cases all the energy went into the primary arc and there was no spark on the secondary. The switching loss was too high. Over 160 years ago, the relationship between switching speed and switching loss in an inductive circuit was recognized.



In 1853, Fizeau [4] provided a solution for the problem. As shown in figure 4, Fizeau placed a capacitor across the contacts. The result was to allow the switch contacts to open with a very low voltage across them, quenching the primary arc rapidly. This is exactly the same action we see today at turn-off for a semiconductor switch where the inductor current is commutated from the switch to a shunt capacitor. Because the voltage across the capacitor is the integral of the current, it takes time for the voltage to rise, allowing us to turn off the switch with very little voltage across it and little loss. It is clear from Fizeau's paper that he knew exactly what the problem was and proceeded to fix it. This was not a serendipitous invention.

His idea immediately increased the performance of induction coils and was universally adopted. He clearly deserves the credit for inventing the capacitor turn-off snubber, which is so widely used to this day. The value of his invention was recognized at the time and in the turn-of-the-century texts referenced above, and he is given full credit. So, Fizeau is the father of soft-switching.

Almost immediately, Ruhmcorff (a noted builder of induction coils of the period) adopted the capacitor snubber and appears also to have built a bi-directional switch arrangement, which put a true AC signal on the primary rather than the pulsating DC used earlier. If this is correct, then Ruhmcorff produced the first DC-AC squarewave inverter with a snubber on the switch.

We tend to think of the induction coil as a laboratory curiosity, but in the late 1800's it had a number of important practical applications. Hertz used it to confirm the existence of electromagnetic waves and Marconi quickly adopted it to make radio transmitters.

Roentgen's X-ray tube (1896) was a vacuum diode which required a high voltage across it to generate X-rays. Early X-ray machines used an induction coil to generate the necessary potential. Of course, connecting a rectifying diode across the output of the induction coil changed it from a DC-AC inverter to a DC-DC converter. A very early power electronic device!

Beginning in the 1860's (Lenoir), and continuing to this day, an induction coil was used to generate the spark to trigger ignition in gas engines. Early on, the induction coil was also a primary tool for generating high potentials for testing electrical insulation materials and for understanding the physics of arc discharges in air and other media.

Improvement of induction coil performance provided some of the earliest developments and understanding of insulating materials. It also brought out the effect of eddy current losses in the core. Faraday and the earliest experimenters used a solid iron core but in 1836 Callan introduced the use of a bundle of iron wires for the core. This is the origin of the laminated core. Callan also introduced the idea of passing a bare copper wire through a bath of liquid resin or other insulator to coat the wire as it was being wound on the coil. This provided turn-to-turn insulation.

## Phase-shifted bridge update

In my January article on soft switching, [5] I mentioned Ron Goldfarb's 1981 POWERCON article on the phase-shift controlled full-bridge circuit [6] and pointed out that this was the earliest published reference I could find. At the end of the article there was a plea for further information from the readers. Although I didn't hear from you, I did find some earlier work nonetheless. In the 1976 PESC proceedings, there is a paper [7] by Allen Ahrens and Hap Cardwell that gives a detailed description of a phase-shifted full-bridge converter. So now we have moved back another five years.

Naturally, I called Hap and asked if he knew of any earlier work and had he applied for any patents. No patents were applied for but the work in the '76 PESC paper was a derivative of some work done several years earlier. Figure 5 shows a circuit that Hap used earlier. Notice that it uses three legs. The two outer legs are fixed either in phase or  $180^\circ$  out of phase with respect to each other. The phase of the center leg is then varied for control. If the two outer legs are  $180^\circ$  out of phase from each other, then varying the center leg phase will cause the output of one supply to go down and the other to go up. What a slick way to build a power supply with an output that swings from + to -.

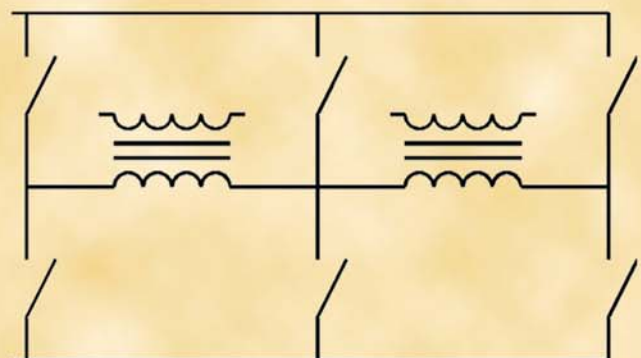


Figure 5. Cardwell circuit

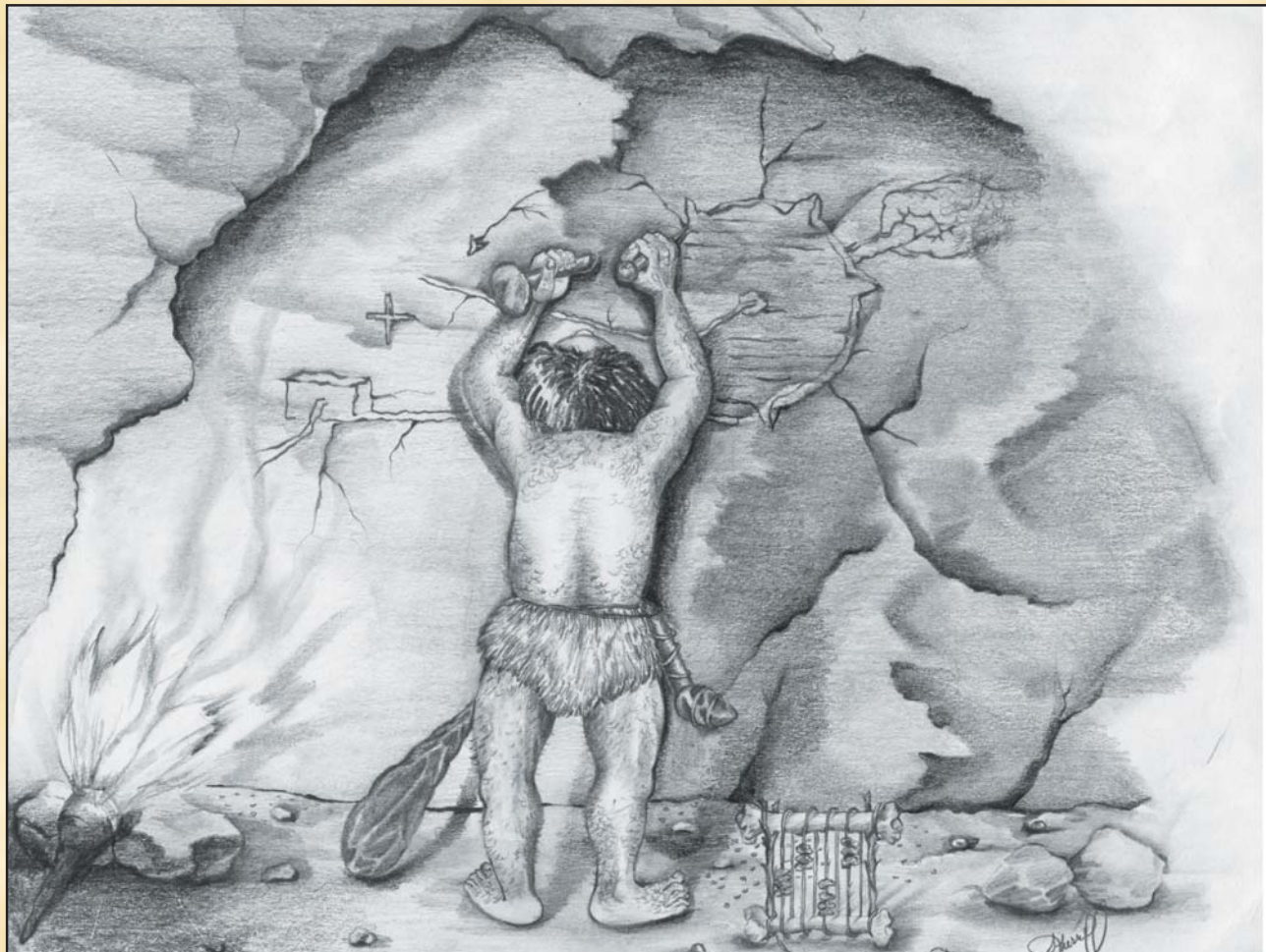
In the early 70s, the switches would have been bipolar junction transistors, because the power MOSFET was not yet derived. Due to storage time effects the need to insert a small dead-time between switch transitions to avoid overlapping conduction would have been obvious. That dead-time would have automatically given at least some degree of soft switching.

Now, a question for SPM readers:

Is Cardwell really the first to use phase-shift control or are there even earlier references? If not, then Hap Cardwell should be recognized for his work.

### Bibliography

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- [6] Goldfarb, R., *A NEW NON-DISSIPATIVE LOAD-LINE SHAPING TECHNIQUE ELIMINATES SWITCHING STRESS IN BRIDGE CONVERTERS*, POWERCON8 proceedings, April 1981, pp. D-4-1 through D4-6
- [7] Ahrens and Cardwell, *ARC DISCHARGE SUPPLY COMPONENT PROTECTION CIRCUITRY*, IEEE Power Electronics Specialists Conference proceedings, June 1976, pp. 326-333



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