Historic Twin-Tesla Lightning Demonstrator Replica

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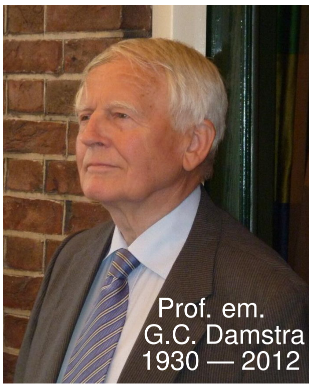
Abstract— The large twin-Tesla generator, designed and built by the late Prof. Damstra, was destroyed by copper thieves early 2013. As it was an excellent demonstrator showing the genesis of lightning strikes, a working replica has been built in a project for the Historic Study Collection Working Group at the University of Twente.

1 Introduction

In 2007 I met emeritus professor Damstra for the first time.

He had been working most of his career in high-current/lightning protection and testing first at Hazemeijer (now:Eaton) in Hengelo (1957) and later at the KEMA in Arnhem (1974) both in the Netherlands. He was appointed part-time professor at the Technical University of Eindhoven in 1991.

I visited him in the old Hazemeijer factory in the Tuindorpstraat.



There I also met a student, Alex Blaj, from Romania, ready to start a PhD at the University of Twente in Enschede on the subject *Protection of Electronics against Lightning* in cooperation with Thales Nederland in Hengelo. From 2009 I had the honor to coach his PhD activities and together we visited prof. Damstra many times to perform lightning related test using old KEMA test equipment. Damstra had reassembled and set it to work there.

The old test-set is described in a paper, [1], essentially describing three installations to generate the phases, A, B and C of the lightning current, shown in Fig. 1.

But in addition to this *serious* test equipment, he also brought several demonstrators, designed and built in his KEMA years, to instruct visitors on the genesis of lightning and related subjects. Some time after the professor passed away, the demonstrators were cannibalized –copper was removed by junks– during an asbestos remediation of the building. This is a pity as the demonstrations were very useful for educating students in the behavior of lightning and other high-voltage effects.

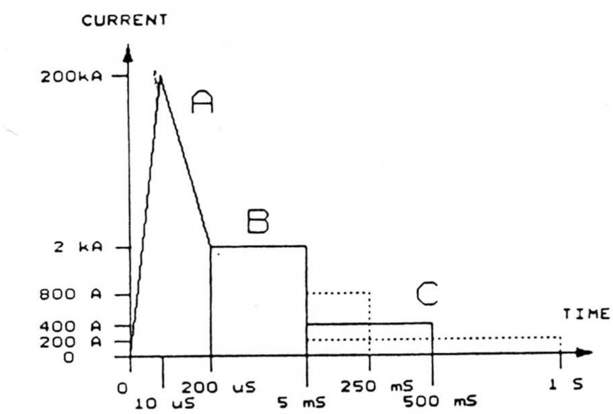


Fig. 1: A, B and C lightning current phases in [1]

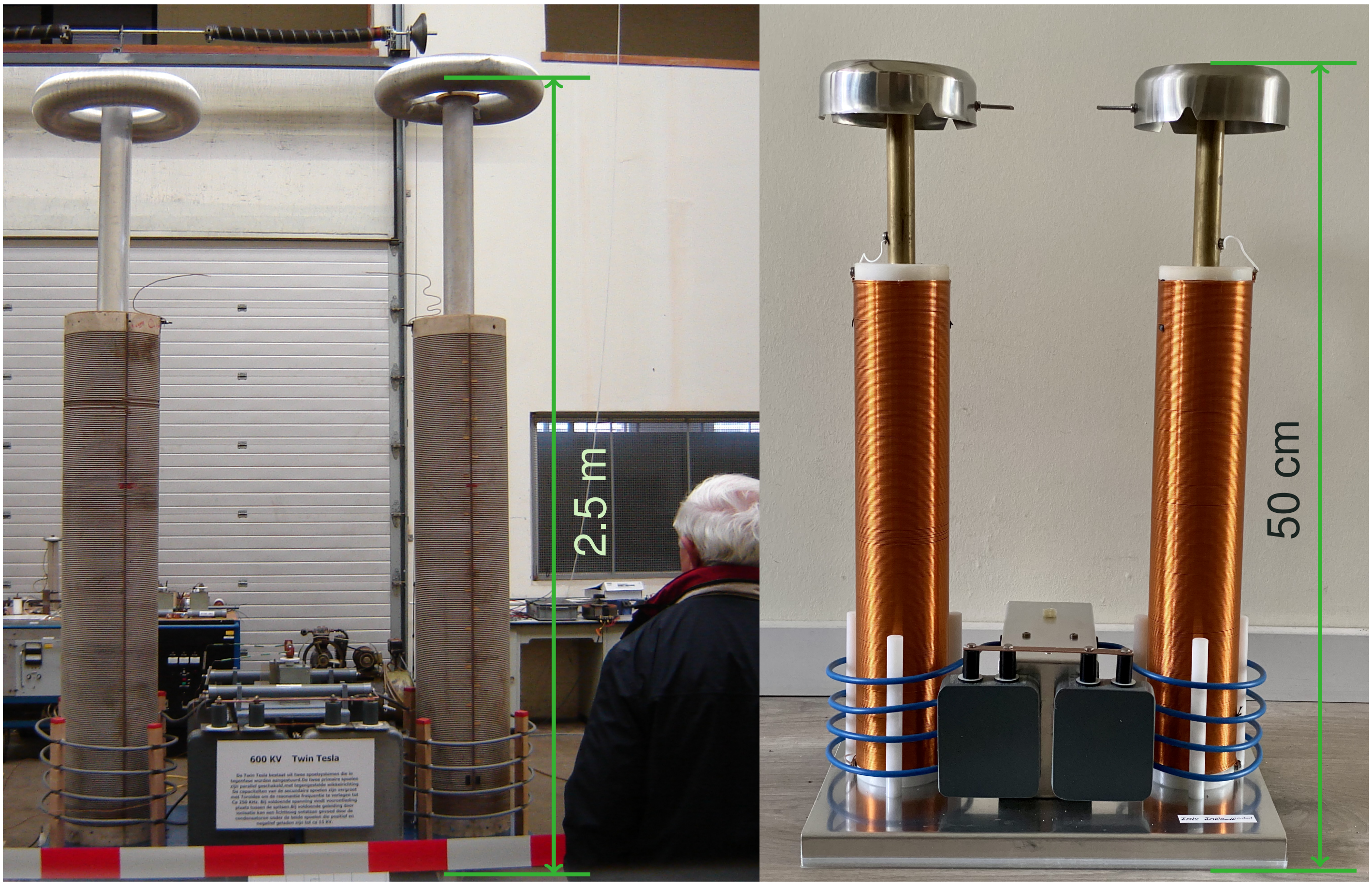
It is the prime task of my current affiliation, the Historic Study Collection Working Group at the Faculty Electrical Engineering, Mathematics and Computer Science (EEMCS) of the University of Twente, to restore important experiments used to teach in the past. I decided to try and rebuild the lost experiments. This paper describes the "replication" of the original Twin-Tesla coil experiment that occupied a space of $1.5 \times 1 \times 2.5$ m^3. The original had an impressive size. For practical reasons and portability, the replica had to be trimmed in size.

2 The replica Twin-Tesla design

Fig. 2 shows pictures of the original –Fig. 2a– and the replica –Fig. 2b– of the historic Twin-Tesla coil demonstrator. As the intention is to use the experiment for teaching and demonstrations, the replica deviates slightly from the exact photo-copy of the original:

- The original spark-gap interrupter is substituted by a solid-state primary driver (see Section 4).
- The tubular toroid capacitive top-hats of the original are replaced by available thin stainless steel cups –actually ash-trays– with an appropriate size.
- The wire spark-gap on top of the original secondary coil bodies is now mounted to these top-hats –using sharpened M3 bolts– .
- The original design had two large high-voltage capacitors on the front and back side. To achieve some similarity with the original, poly vinyl chloride (PVC) dummy's are installed on the replica (front side only).

The number of turns –4– of both primary coils could be kept the same. Fig. 3 on page 3 shows the essential dimensions of the replica.



(a) Original Twin Tesla **(b)** Replica Twin Tesla

Fig. 2: Replica of Twin Tesla generator built to scale 1:5

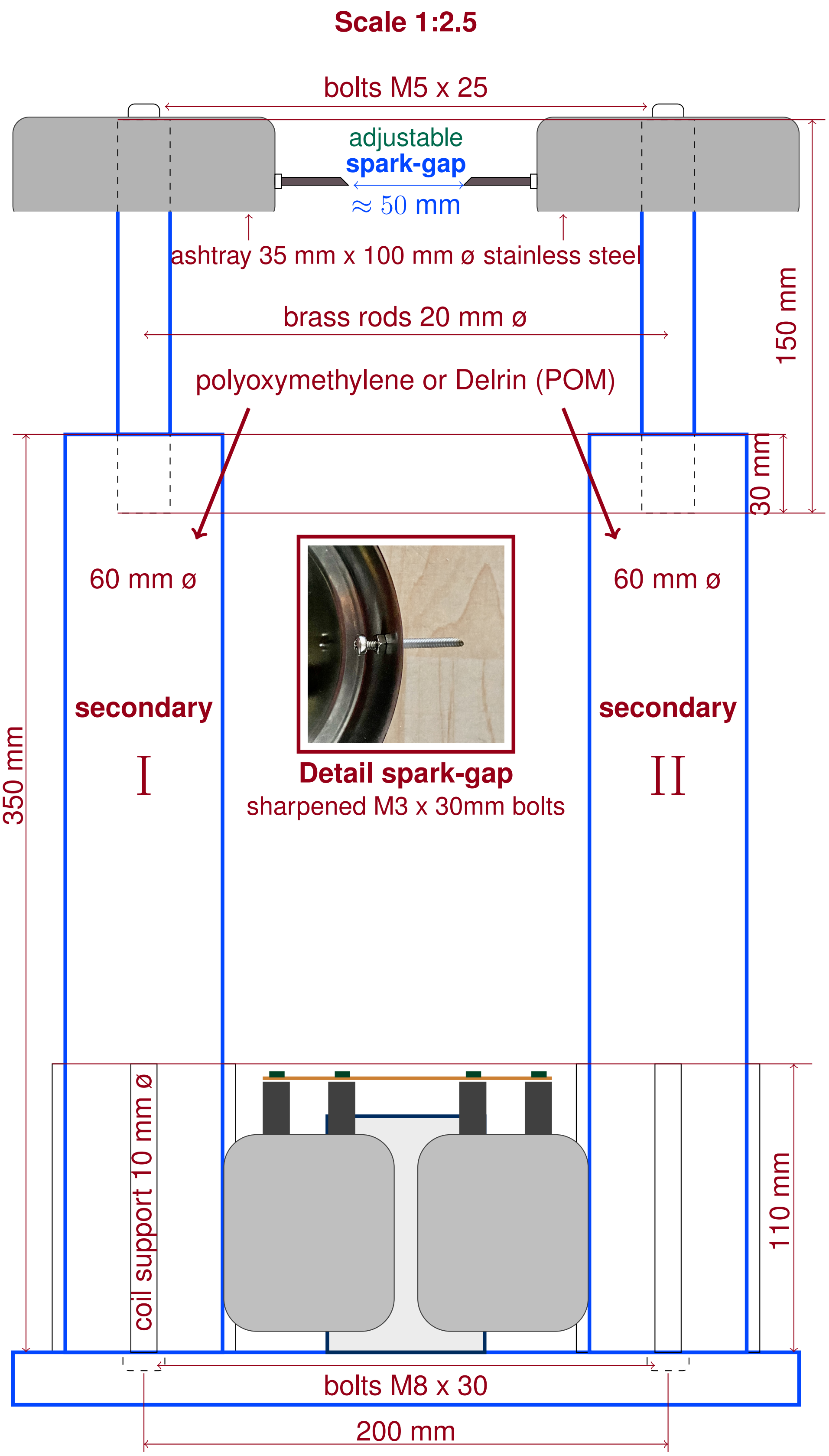


Fig. 3: Drawing of the solid state twin Tesla coil (SSTTC) replica with important measures

3 The original Twin-Tesla design

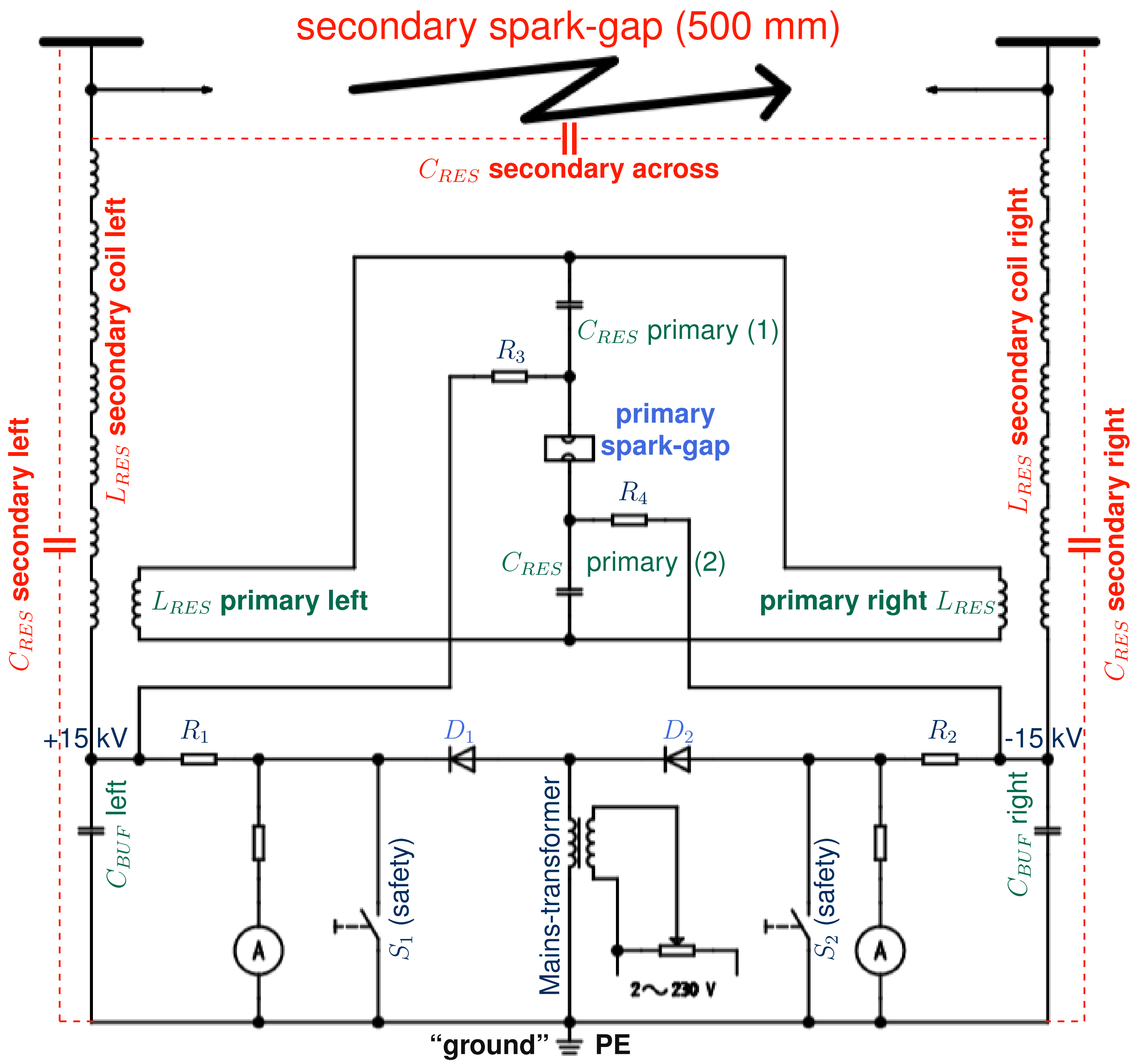


Fig. 4: Annotated original schematic diagram of the Twin-Tesla generator

The circuit diagram in Fig. 4 shows that this twin-Tesla systeem indeed has two separate Tesla coils driven by two parallel primary coils with series capacitors and a single central spark gap.

This circuit operates as follows:

1. The two top-loads/toroids each form a resonant capacitor with each other, as C_{RES}, **secondary across**, and as C_{RES}, **secondary left** and **secondary right** and **"ground"**, protective earth (**PE**). These capacitors create a series as well as parallel resonant circuit with the two secondary coils, L_{RES} **secondary**, **left** and **right**. This resonant system determines the frequency at which the twin-Tesla system will operate;

2. The bottom-central Mains-transformer charges the two *buffer*-capacitors, C_{BUF}, **left** and **right**, to a high **positive** and **negative** voltage of approximately 15 kV via resistors R_1 and R_2 respectively. These voltages also "pre-load" the two secondary

$L_{RES} - C_{RES}$ **secondary** systems to a differential, but direct current (DC), voltage of **30 kV**. In itself this voltage can not produce a spark between the two toroids (50 cm);

3. These two high C_{BUF} voltages also charge the capacitors C_{RES} **primary**, (1) and (2) via two more resistors, R_3, R_4 respectively up to a voltage that will trigger the **primary spark-gap**;

4. As soon as the **primary spark-gap** breaks down, a low-impedance plasma-channel essentially short circuits the two series resonant circuits C_{RES}/L_{RES} **primary** (1) and (2). The electric energy stored in the two C_{RES} capacitors will convert into magnetic energy in the two L_{RES} **primary** coils and back, producing a ringing electromagnetic (EM)-field exciting the L_{RES} **secondary** coils, until dissipated. At that point the **primary spark-gap** will extinguish. All details of this process can be found in the thesis of C. Gerekos at the Université Libre de Bruxelles, [2];

5. Both L_{RES} **primary** coils although in parallel, are wound in opposite directions;

6. Consequently, their EM-fields will produce voltages of opposite polarity in the L_{RES} **secondary** coils.

7. This produces a high differential voltage between the two toroids –over C_{RES} **across**–. According to the description on the machine, **600 kV**;

8. This will lead to a spark-discharge –a plasma channel– between the two wires[1] connected to the toroids, forming the **secondary spark-gap**;

9. This initially tiny plasma channel can be compared to the pre-discharge, a "streamer", preceding a lightning stroke[2]. It produces a low-impedance channel between the two toroids;

10. Once the conductive channel is present between the toroids, the differential **30 kV** present between the four separate buffer capacitors together estimated[3] at $0.4\ \mu$F. C_{BUF}, **left** and **right** is effectively short circuited. This produces a huge *explosive* discharge, visible in Fig. 5a. The energy in to buffer capacitors is estimated in Equation 1;

$$E = \frac{C_{BUF} V_{BUF}^2}{2} = 45 \quad \text{J} \tag{1}$$

11. To prevent accidents, the switches S_1 and S_2 are present. These are used to discharge the C_{BUF} and C_{RES} capacitors when the machine needs maintenance.

(a) Explosion!

(b) – –

Fig. 5: "Brainwashing" a colleague

1 In Fig. 2a on page 2 these wires are visible.
2 More information can be found on the web, e.g. at `https://ghrc.nsstc.nasa.gov/home/lightning/home/primer/primer2.html`
3 Prof. Damstra once told me *each* buffer capacitor set consisted of two $0.1\ \mu$F 25 kV capacitors – the large grey blocks on both sides of the machine–.

4 The replica circuitry

The drawing in Fig. 3 on page 3 shows the measures relevant for the functional behavior of the replica.

4.1 The secondary coils

The secondary coils are wound using 0.65 mm ø – American wire gauge (AWG) 22 – enameled copper wire. Starting 1 cm from one edge of the 60 mm ø polyoxymethylene or Delrin (POM) columns up to 1 cm from the other end. I used two M3 bolts with a soldering lug on each side to connect the wire. Approximately 460 turns on each column.

I wound both columns in the *same* direction. Note the difference between top and bottom of the columns. The bottom has a M8 threaded hole. The top has a 20 mm ø hole for the toroid support. Starting from the bottom, I turned the POM column counter-clockwise to wind the coil.

4.2 The primary coils

The primary coils each have 4 complete turns and are wound using 2.6 mm ø –AWG 10– solid copper, insulated –blue– installation wire. The turns have an inner diameter of 100 mm. The three coil supports around each secondary coil in Fig. 3 on page 3 are positioned such that the primary coil stays in place based on some spring action in them. In fact, due to the stiffness of the wire, coil supports are not strictly necessary. The supports are included to make the replica look more like the original. For that same reason, there is no need for e.g. ty-raps (Figs. 6 and 7).

Fig. 6: Replica primaries detail

Fig. 7: Primary support's positions

Both primary coils are electrically *in parallel*. But wound in *opposite* directions. Look at the primary wires emerging from the top of the central electronics compartment –the aluminum structure in the middle–. Both pass *in front* of the secondaries –bottom in Fig. 7–. The reason is that the secondary coils are wound identically and we want the induced secondary voltages to *add-up* at the top-loads/toroids.

This is no different in the original twin-Tesla system, shown in Fig. 8.

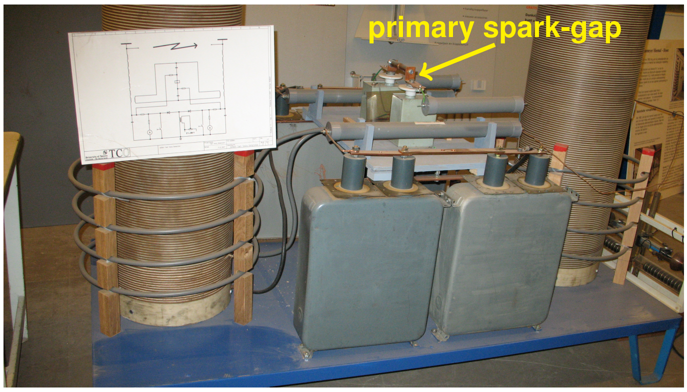


Fig. 8: Original primaries detail

4.3 The replica driver is solid-state

The original twin-Tesla is a traditional Tesla coil with primary and secondary coil-capacitor sets tuned to the same frequency, [2, Section 3.3, pages 15-23].

For the replica, I chose the solid-state approach: the secondary coil capacitor combination, $L_{RES_{SECONDARY}}$ and the various components of $C_{RES_{SECONDARY}}$ in Fig. 4, determines the resonant frequency of the system.

The circuit diagram, working on 230VAC[4] is shown in Fig. 9.

The secondary current is measured and fed back to the active circuitry, in this case, a single insulated gate bipolar transistor (IGBT). This IGBT then amplifies it and drives the two parallel primary coils in a positive feedback fashion.

This circuit is called an *Armstrong* or *Meißner* oscillator[5]. The circuit diagram is shown in Fig. 9.

The secondary coils are not shown. Secondary II is the right hand side coil in Figs. 2b and 3. This coil is used for feedback to the IGBT.

The transformer –L1– is wound on a ferrite ring TX22/14/6.4 3E27 available e.g. at Farnell, order code #1784174.

This transformer separates the primary circuit, which is directly connected to the mains power system, from the secondary coils.

Touching the secondary top-loads will stop the oscillation but is not lethal... **Until you decide to add the "Explosive discharge" related components, see Section: 7 page 13.**

Note: only the bottom terminal of secondary II is fed back to the IGBT. The bottom connection of secondary I , at this point, is directly attached to the aluminum pedestal i.e. protective earth (**PE**).

Filtering a Tesla coil is difficult as the huge electric fields *into the world* will create common-mode (CM)-currents on the mains wires anyway.

There is some differential-mode (DM) filtering provided by $C1 = 2.2$ μF in combination with the resistance of $LMP1 = 230$ V 50 W.

$C1$ actually forms a current boundary (CB) between the Armstrong oscillator and the outside world. For more details on CBs, see [3].

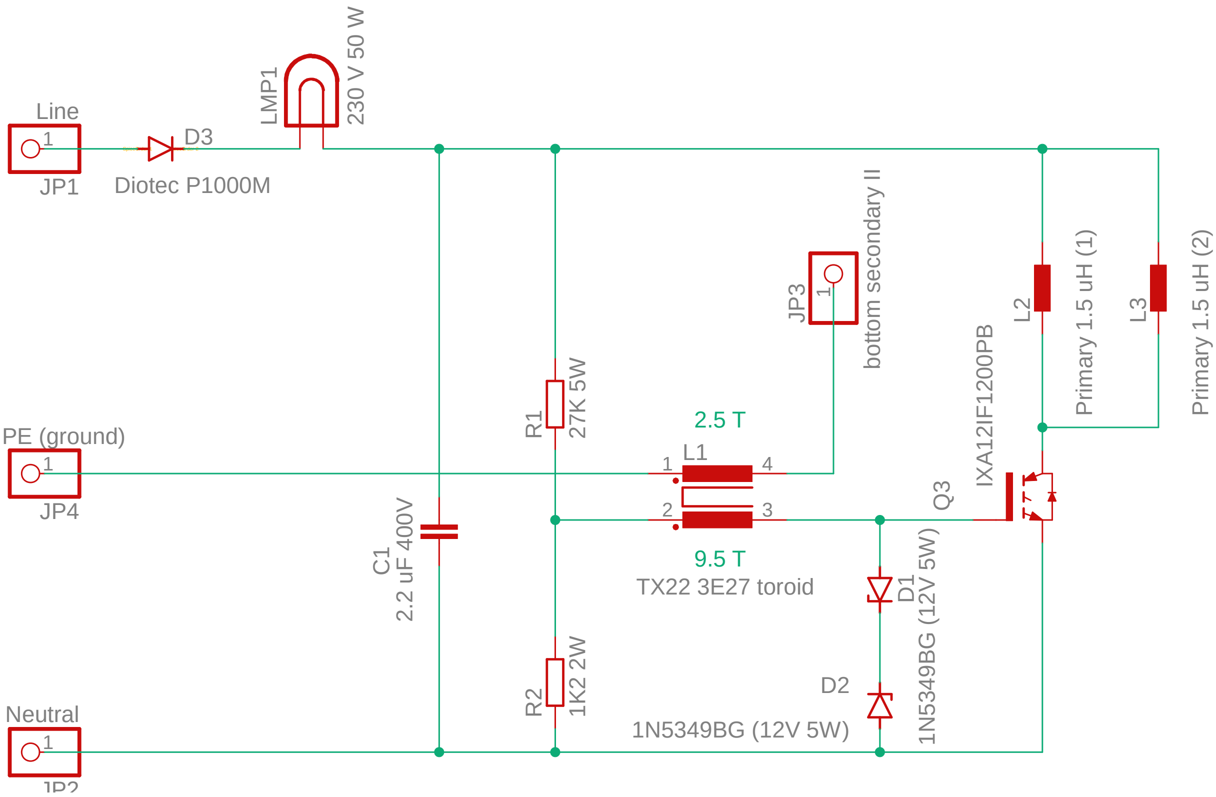


Fig. 9: Armstrong Oscillator driving the primary coils of the solid state twin Tesla coil (SSTTC)

4 It is inspired by the 120 VAC circuit shown at https://www.instructables.com/Simplest-POWERFUL-Solid-State-Tesla-Coil-SSTC/. The "ballast" coil shown in the original is replaced with a 50W halogen lightbulb. A 50W resistor might be an option.

5 See https://www.elprocus.com/armstrong-oscillator-circuit-working-application/#:~:text=An%20Armstrong%20oscillator%20(also%20known,other%20active%20(amplifying)%20devices.

5 Measurements

5.1 Performance

The system now works as far as the basic Tesla coil performance is concerned.

The spark-gap at the top-loads on the secondary coil is adjusted to 50 mm. As visible in Fig. 10, lightning-like streamers flow from one side to the other.

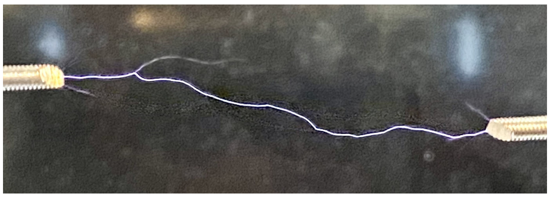


Fig. 10: Standard 50 mm gapwidth

By turning one or both top-loads a little, the gap can be increased to 66 mm. In Fig. 11 "connecting" sparks are no longer visible.

Fig. 11: Increased –66 mm– gapwidth

These sparks look more like those from a single Tesla coil as shown in Fig. 12

Fig. 12: "Sword" fashion sparks, single Tesla coil

5.2 Frequency of operation

The dominant frequency of operation lies around $F_{RES} \approx 1035$ kHz i.e. the medium wave –530 to 1610 kHz– (MW)-band.

This frequency depends on conductors and high permittivity, ε, material near the secondary coils and top-loads e.g. water vapor.
A change in permittivity of the environment of the top-loads will modify the values of the secondary resonant capacitors and hence change the resonant frequency.

The oscilloscope[6] analysed the frequency behavior of the solid state twin Tesla coil (SSTTC) and shows a lot of noise around the main frequency in Fig. 13, only 20 dB down with respect to the dominant frequency.

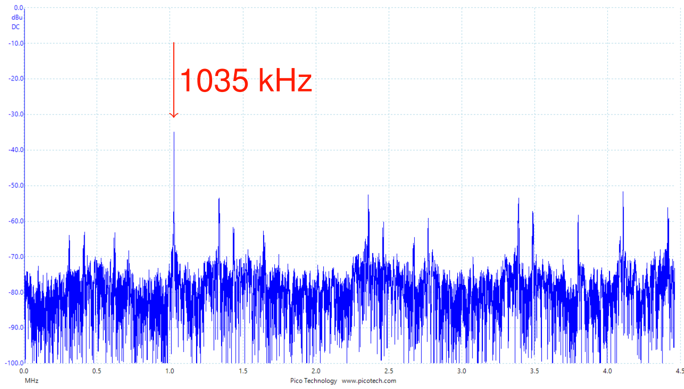


Fig. 13: Main frequency 1035 kHz, very noisy spectrum

5.3 Coil impedances

One completed secondary coil measures $L_{RES_{SECONDARY}} = 2.2$ mH in series with $R_{SECONDARY} = 4.5\ \Omega$.

One primary coil measures $L_{PRIMARY} = 1.5\ \mu$H. The impedance at the operating frequency is then given by Equation 2.

$$|Z_{L_{PRIMARY}}| = 2\pi F_{RES} \cdot L_{PRIMARY} \approx 10 \quad \Omega \quad (2)$$

[6] A Pico Technology 5244D MSO

In a different, way more complicated, example design I looked at earlier[7], the advice was given to keep the primary coil impedance at about $|Z_{F_{RES}}| \geq 6\Omega$ to protect the driving IGBT.

Although that design is not suitable as only frequencies $F_{RES} \leq 400$ kHz can be handled, I think the advice may be applicable here.

My design has two identical primary coils in parallel, i.e. $|Z_{PRIMARIES}| \approx 5\ \Omega$.

I went ahead with the used IGBT[8] considering the relatively large series impedance of the halogen bulb and relatively low capacitance of $C1 = 2.2\ \mu$F in the schematic diagram in Fig. 9 on page 7.

5.4 Time domain behavior

As can be noticed from the schematic diagram in Fig. 9 on page 7, the circuit runs on the single phase rectified mains voltage. It is current limited by the halogen light-bulb and only has a small capacitor.

In Fig. 14 a measurement[9] of the mains voltage and a band filtered version of its neutral wire. It shows that sparks of the SSTTC only occur in the top of the positive sine wave (timebase: 2 ms/div).

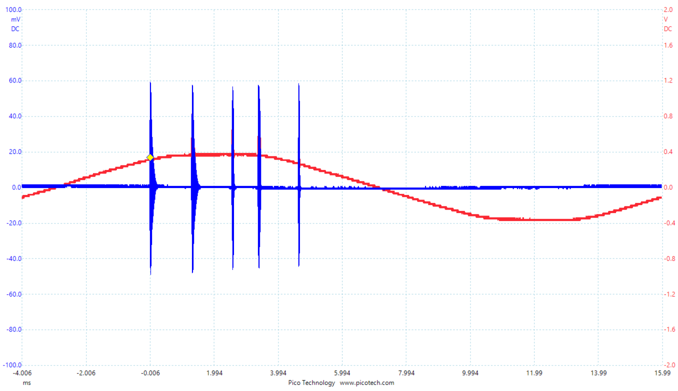


Fig. 14: Sparking bursts relative to mains voltage

Fig. 15 shows one of these bursts using a timebase of 50 µs/div.

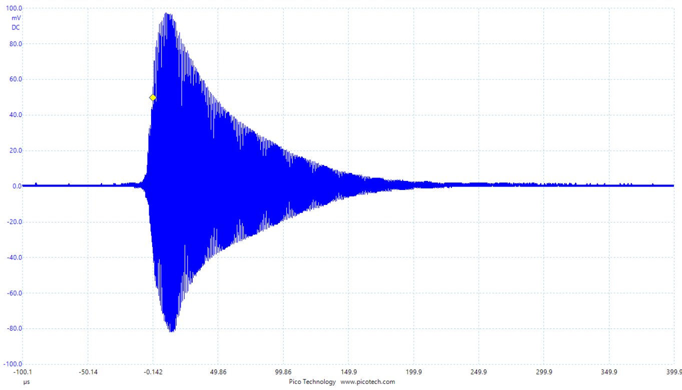


Fig. 15: The first burst in Fig. 14

Fig. 16 finally shows the start-up portion of a burst at a timebase of 1 µs/div. This shows the waveform is not a nice, smooth sinewave but has many harmonics.

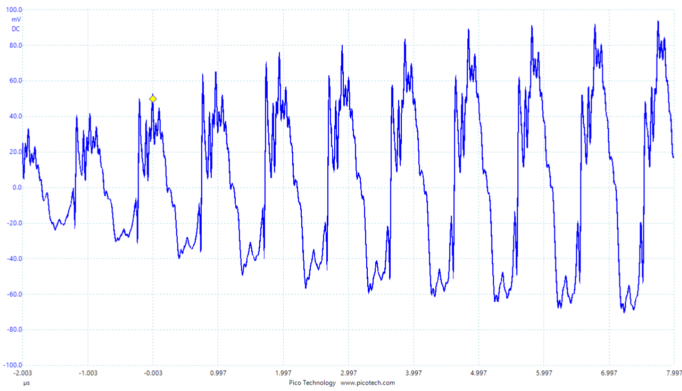


Fig. 16: Detail of burst onset in Fig. 15

5.5 Power consumption

Power consumed[10] : 23 W (including 230VAC/50 W series halogen bulb).

[7] See https://www.instructables.com/Building-the-Ultimate-Solid-State-Tesla-Coil-MUSIC/.

[8] Since the IXYS IXA12IF1200PB can handle 20 A and has a V_{CES} of 1200 V as specified in https://www.tme.com/Document/59ef922fa3f70bc7062dadf3f874a179/IXA12IF1200PB.pdf.

[9] The measurement was performed using a special test device that has a 1/1000 voltage divider on the mains voltage **Line** conductor and a high-pass filter that provides, in this case, a 1/50 version of the mains **Neutral** conductor at frequencies above $F_{high-pass} \approx 2$ kHz (band limited to approximately 7 MHz), [4]

[10] Measured using the GT-PM-05 from Globaltronic GmbH & Co, Hamburg, Germany.

6 Building the “huge explosive discharge”

6.1 The Cockcroft-Walton circuit

The “huge explosive discharge” referred to in Fig. 5 on page 5 can be achieved with the SSTTC by creating a DC voltage difference between the secondary coil top-loads.

For that purpose first one and finally both bottom ends of the secondary coils are connected to ground (**PE**, later **Neutral**) through a capacitor (-bank) just as was done in the original (Fig. 4, page 4).

Two experiments were performed using a capacitor bank connected to the bottom ground wire of the secondary I coil only.

Initially using a $C_{BUF} = 25$ μF capacitor-bank –four 100 μF capacitors in series– charged to a voltage near 1200 V –measured 1170 V– *assuming* that would be sufficient for the 50 mm wide spark-gap.

The reason for the need to connect 4 capacitors in series is their maximum charge voltage of 400 V.

The stored energy in this 25 μF capacitor at 1170 V can be calculated using Equation 3.

$$E = \frac{C_{BUF} V_{BUF}^2}{2} = 17 \quad \text{J} \tag{3}$$

This is about 40% of the estimated 45 J in the original twin-Tesla.

The *assumption* this 1200 V would be sufficient to bridge the 50 mm spark-gap was based on the statement made in [1] that a 30 cm (!) spark length could be maintained using a 1400 V DC source[11].

The *assumption* was wrong: only a 22 mm long *explosive* spark could be produced with 1200 V.

To charge this series of capacitors, the familiar voltage multiplier known as the Cockcroft-Walton circuit was used in all experiments[12]. See Fig. 17.

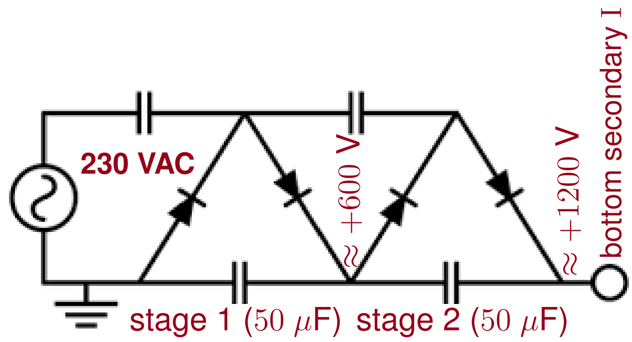


Fig. 17: Two stage Cockcroft-Walton voltage multiplier

For this first experiment a two-stage Cockcroft-Walton generator was needed. On a 230 V alternating current (AC) mains, each stage theoretically doubles the peak mains voltage of $230 \cdot \sqrt{2} = 325$ V i.e. 650 V so each stage is composed of two 100 μF capacitors.

In order to remove a possible remaining lethal charge in the capacitors, all have bleeder resistors[13] (100 kΩ per 100 μF capacitor).

This lowers the achievable maximum voltage somewhat. The actual measured voltage of the two stage Cockcroft-Walton is 1170 V.

The second experiment used a 16.7 μF capacitor-bank –three stage, six 100 μF capacitors in series– charged to a voltage of almost 1600 V –measured 1540 V–. This could produce a 33 mm *explosive* spark.

The energy contained in the six 100 μF capacitors, using Equation 3, is 20 J.

The increase of the –measured– Cockcroft-Walton voltage multiplier voltage from 1170 to 1540 V allowed an increased spark-length from 22 to 33 mm.

11 This was related to Damstra’s work with the lightning B-pulse generator: a machine producing a DC 2000 A discharge, see Fig. 1, page 1.

12 see https://en.wikipedia.org/wiki/Cockcroft%E2%80%93Walton_generator or https://www.youtube.com/watch?v=ep3D_LC2UzU for a lecture.

13 An additional effect is the even distribution of charge over all capacitors.

This suggest a –more or less– linear relationship between the voltage difference of the top-loads and the bridgeable gap-width.

For the third experiment the voltage difference is increased to almost 2400 V to obtain a 50 mm explosive discharge.

The third and final experiment uses two parallel Cockcroft-Walton generators to obtain both a positive and a negative 1170 V as shown in Fig. 18.

This generator, with Equation 3, stores approximately 34 J of energy when fully charged.

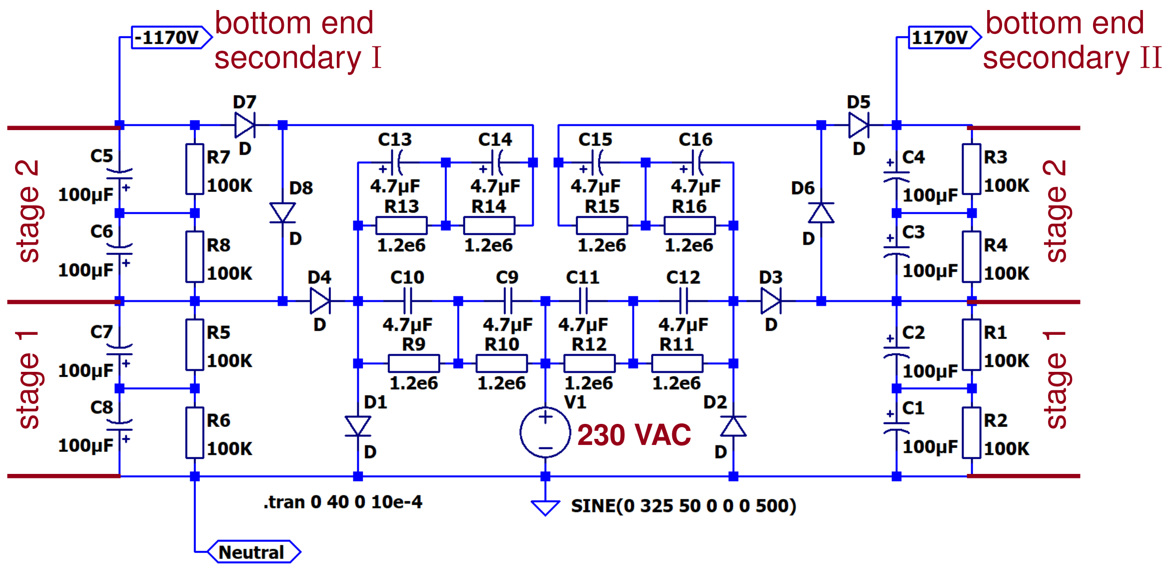


Fig. 18: A dual two-stage Cockcroft-Walton to obtain + and - 1170 V, energy: 34 J (75% of original)

As can be observed in Fig. 18, the capacitors in the second leg of each Cockcroft-Walton generator are much smaller: $4.7\ \mu$F. Consequently the bleeder resistors are larger. Smaller capacitors limit the mains-supply current. The peak load on the mains is around 200 mA$_{\text{eff}}$. Using $100\ \mu$F versions here could certainly blow fuses. The effect is that the Cockcroft-Walton generators need around 10 seconds to attain their peak voltages.

The number of $100\ \mu$F capacitors now reached 8. Bringing the energy available for the explosive discharge to –Equation 3– **34 J**.

Insiders may have noticed Fig. 18 is actually a Spice® model. It can be simulated using the free LTspice® software from Analog Devices[14].

Feeding the model with 230 V 50 Hz for 10 seconds provides the graphs in Fig. 19.

The bleeder resistors discharge the –lethal– ≈ 2400 V voltage between the top-loads in about 30 seconds. See Fig. 19.

This is in the absence of an explosive discharge.

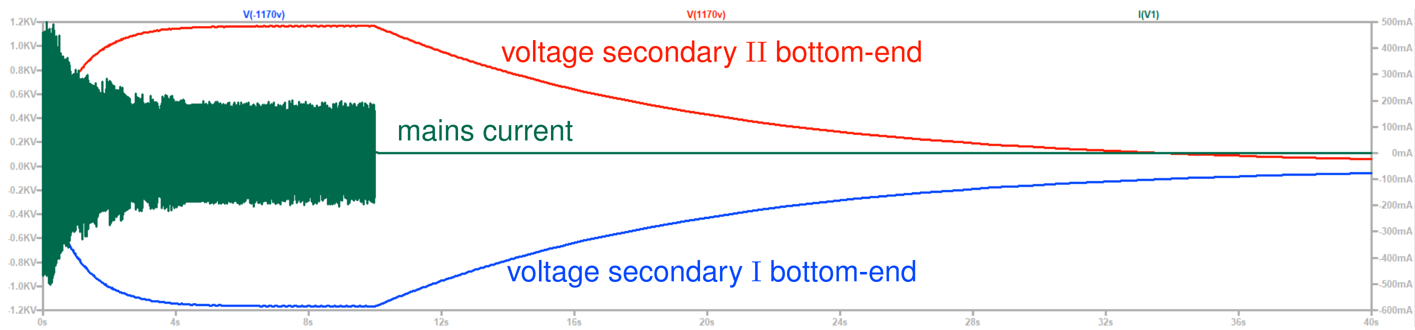


Fig. 19: Simulation of the voltages of and current into the dual Cockcroft-Walton circuit of Fig. 18

14 See: https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html

6.2 The 22 mm *explosion* = 1.2 kV

As mentioned, the first experiment was performed with a two-stage Cockcroft-Walton. Reaching a voltage of 1170 V over $25\ \mu$F.

At the initial 50 mm spark gap, mentioned in Section 5, no explosive discharge could be produced.

Reducing the gap to 22 mm did produce the “bang”. The effect is shown in Fig. 20.

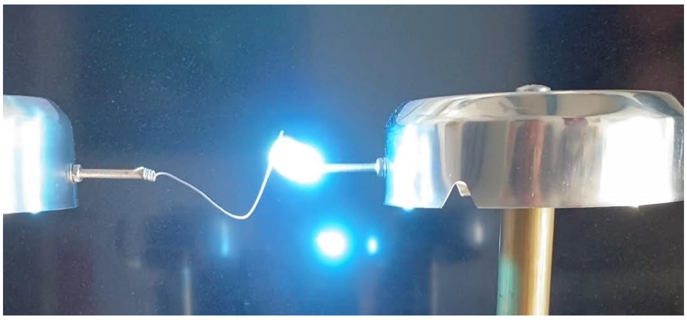
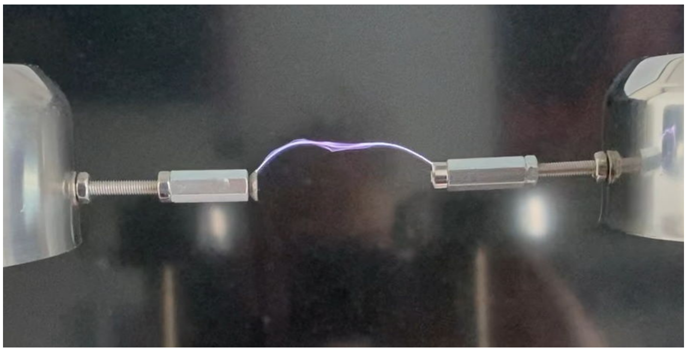


Fig. 20: Nice explosion but only 22 mm wide

But 22 mm is too small for a *convincing* replica.

6.3 The 33 mm *explosion* =1.6 kV



(a) Arc discharge before. . .

(b) The explosion

Fig. 21: 33 mm explosion preceded by tiny arc. . .

As a next step, a third stage was added to the Cockcroft-Walton. This allowed a gap of 33 mm.

Two pictures, one just before the big discharge and the discharge itself appear in Fig.’s 21a and 21b.

6.4 Stretching to the *full 50 mm* gap

For this third experiment both secondary coil bottom ends are DC shifted as shown in Section 7.

One positive and one negative as shown in Fig.’s 18 and 19.

The desired 50 mm *explosive* spark discharge can now be produced as shown in Fig. 22b.

(a) Preparing to brainwash another volunteer

(b) Zapping!

(c) Mission almost accomplished

(d) Done!

Fig. 22: The final 50 mm explosive discharge

7 Connection diagram for the dual Cockcroft-Walton circuit

7.1 A word of caution

Adding the Cockcroft-Walton voltage multiplier, essentially, adding charged capacitors makes the SSTTC dangerous to touch. **Watch out with visitors!** Install warning signs like Fig. 24.

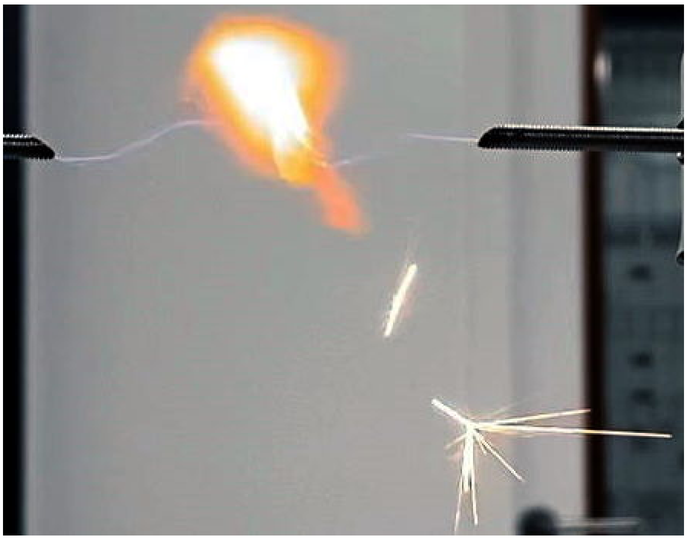


Fig. 23: Explosive sparks, high energy

As soon as the (dual) Cockcroft-Walton circuit is built in, the secondary coils and top-loads will no longer be safe to touch.

The metal base structure and electronics compartment are connected to the **PE** conductor of the mains cord.

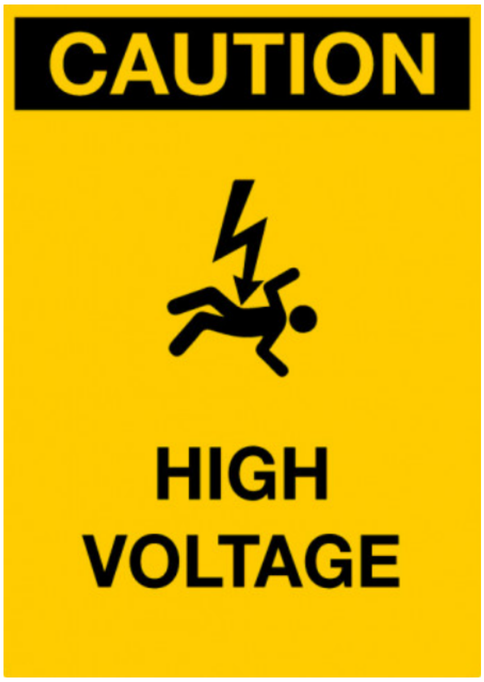


Fig. 24: Possible warning sign

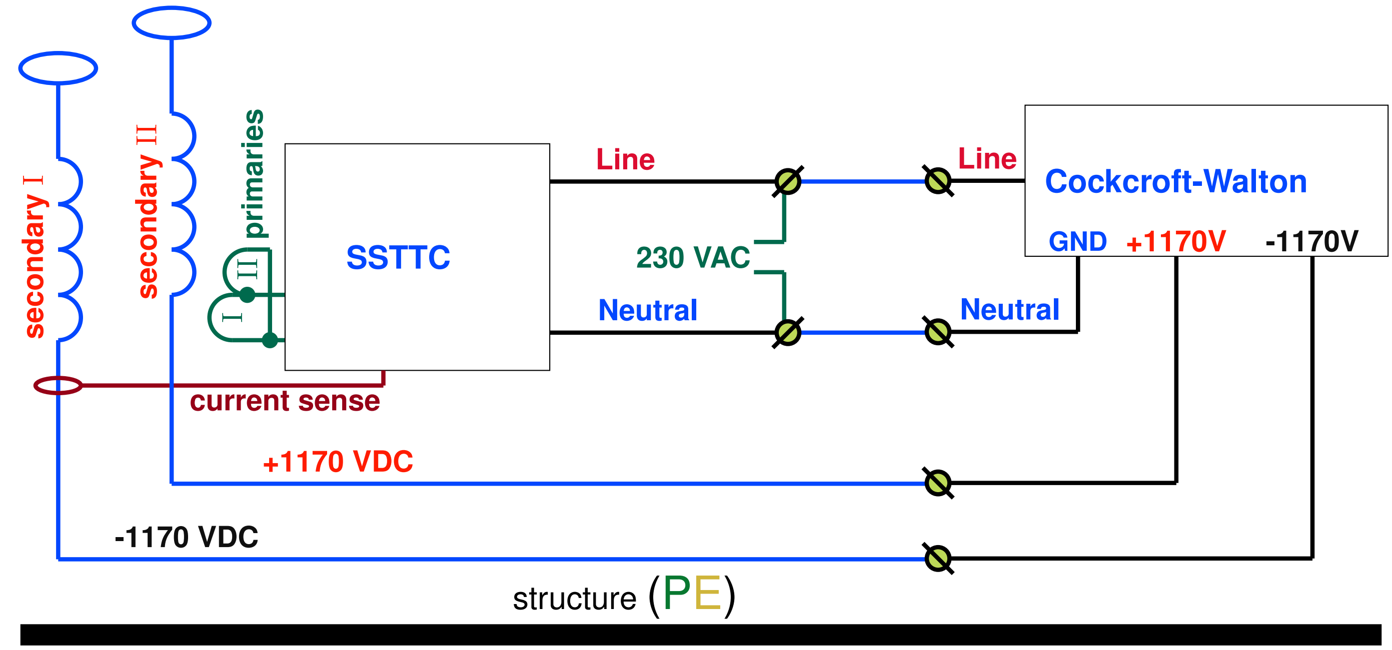


Fig. 25: SSTTC with dual Cockcroft-Walton generator

8 Adding touch-control for interactive display

8.1 Continuous operation unwise

When producing sparks, the SSTTC creates EM-interference in its environment and at the same time produces ozone.

So, the operation must be limited to “very incidental”.

8.2 Touch control

At the University of Twente the SSTTC will be displayed in a glass showcase.

To enable interaction with visitors, a touch sensitive plate is added.

The control of the SSTTC is performed by a programmable intelligent computer (PIC) 12F629 processor and the program is layed out as a state machine with the following (6) states:

0. After power on of the SSTTC with its main power switch, the machine waits for a visitor’s touch.
   A green light emitting diode (LED) shows that the machine is ready for a new demonstration cycle;

1. The visitor starts the demonstration cycle by touching the insulated sensor with one hand;

2. Immediately upon touching the sensor the SSTTC will produce the high-voltage, but small, sparks for 0.5 seconds as touch-acknowledgment feedback to the visitor.
   The green LED is replaced by a red LED to show the demonstration cycle is active. It will remain red up to and including state 5;

3. The SSTTC power is now switched off while the Cockcroft-Walton multiplier is switched for 12 seconds to fully charge the 8 $100\ \mu$F capacitors;

4. The “big-bang” discharge is now initiated using the SSTTC small sparks –a sub-state machine of state 4–;
   (a) Initially with a 20 ms duration series of sparks followed by 300 ms with no sparks;
   (b) Then a 40 ms series of sparks is produced followed by 300 ms without sparks;
   (c) This is followed with 100 ms of sparks with 300 ms silence;
   (d) Next: 200 ms of sparks + 300 ms silence;
   (e) Finally 400 ms of SSTTC sparks are produced.

   This five step sequence with increasing duration of small, high voltage –but low-current– sparks, let us call them *streamers* forming tiny *plasma channels*, has the intention to show that only the right *plasma channel* will start the discharge of the essentially DC charged capacitors.
   The 55 mm distance between the SSTTC top-electrodes in itself is to wide for the roughly 2300 VDC to initiate a spark by itself;

5. After the “big-bang” discharge, Both the SSTTC and the Cockcroft-Walton are switched of for 45 seconds.
   This prevents the over-enthusiastic visitor from triggering the machine at minimum time intervals.

The SSTTC has a small red push-button switch which allows the PIC to be reset to the initial, *green LED*, waiting for touchpad state.

This serves to enable demonstrations for students at a faster rate.

8.3 The electronics

The section with the PIC runs on a separate 5 V power supply which is insulated from the mains.

The two outputs, pins 6 and 7, drive opto-coupler triacs that drive the two power-triacs that switch the SSTTC and Cockcroft-Walton circuits.

A high level at any of these outputs will switch on the respective triac.

Pin 6 drives the SSTTC circuit, pin 7 drives the Cockcroft-Walton generator.

These power triacs have an internal ceramic insulation between the mains connected parts and the heatsink-tab.

These can therefore be bolted to the aluminum structure without insulation.

The touch-sensor circuit is a free running 7555 oscillator, IC2 in the schematic diagram in Fig. 28 on page 18.

The oscillation frequency depends on the capacitance of the sensor, shown in Fig. 26.

Fig. 26: The touchsensor

The sensor is a 50 x 80 mm rectangular section of dual sided copper clad FR4 printed circuit board (PCB) material where one side serves as sensor plate while the other is used as ground reference plane (GRP).

The sensor has a measured capacitance of 120 pF.

Note that the capacitance of the used RG-58 Bayonet-Neill-Concelman (BNC) cable, 100 pf for a 1 m section, must be added to the sensor capacitance.

These 220 pF in combination with the $10\ \mathrm{M}\Omega$, R8 in the circuit diagram of Fig. 28, will result in a 300 Hz square wave at the sensor input of the PIC (pin 2).

The high-to-low transitions of this square wave trigger an interrupt which is counted using the internal real-time clock, ticking at 20 ms intervals.

The number of sensor interrupts is 6 when not touched.

As soon as this number of interrupts drops below 5, a touch action is registered.

This then starts the state machine described in Subsection 8.2.

The state machine timing is derived directly from the internal real-time clock.

8.4 Additional shielding

Initial experiments have shown that the environment “above the bottom GRP in Fig. 3 is to noisy for reliable operation of the electronics shown in Fig. 28.

The PCB with these electronics had to be moved below the GRP.

For that reason an extra “U”-shaped bottom plate is made that fits inside (and is bolted to) the original as shown in Fig. 27.

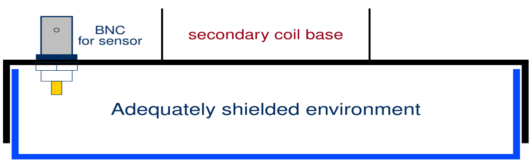


Fig. 27: Additional GRP (blue)

8.5 Firmware

Just to have it available, the firmware to be installed into the PIC 12F629 is shown here in hexadecimal form as Table 1.

Table 1: PIC 12F629 Firmware in hexadecimal format

:100030002108A8002208A9002308AA0083128C30F6
:100040008400001C25280C1853288B1D29280B1808
:1000500042282608840027 08A0002808A1002908B3
:10006000A2002A08A3002B088A00250E8300831211
:10007000240EA51883160900FF2383169000003074
:100080008A00AC290B10831685168312851A49281D
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:1000A0000B108A1129280C1031088F0030088E009F
:1000B0002C0803196528013A03197B28033A031910
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:1000D0000511831605108312051 02F082E02031830
:1000E00077280130AC0083160511831205 15B30182
:1000F000B201AE018E2983169612831 28B158316D8
:100100001616851083128514831605108312 0510A8
:100110008316051183120515B20A0319B30AB30831
:10012000031D96283208183C0318A228B301B20117
:100130008316851083128510831605108312 05100F
:100140000230AC008E2983169612831 28B1583160B
:100150001616051083120514831685108312851058
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:100190008316851083128514 8E2983169612831276
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:10025000B301B2010430AD008316851083128514FA
:100260005F29B308031D38293208093C03183C29CB
:10027000831685108312 8510B308031D43293208A5

Continued on next page

Table 1: PIC 12F629 Firmware in hexadecimal format (cont'd)

:10028000183C03184B29B301B2010530AD008316A9
:100290008510831285145F29B308031D5329320882
:1002A000133C03185F29831685108312851083166B
:1002B000051083120510B301B2010430AC008E2981
:1002C0008316961283128B15831616160510831249
:1002D000051083168510831285108316051183126D
:1002E0000515B20A0319B30A3308073C03188E290F
:1002F000FF3A031D7F293208C93C03188E29B30138
:10030000B201AC010630AE008B15831696160510AF
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:100320008A112928831685108312851083160510DB
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:10036000990092299F29AC01AD010C30A0008101B8
:10037000813084000008F0390738800064000008EC
:10038000F739A019F03920048000640083160C149A
:10039000011383128B1583169616011383128B1586
:1003A00083161616C03083128B0483160511831230
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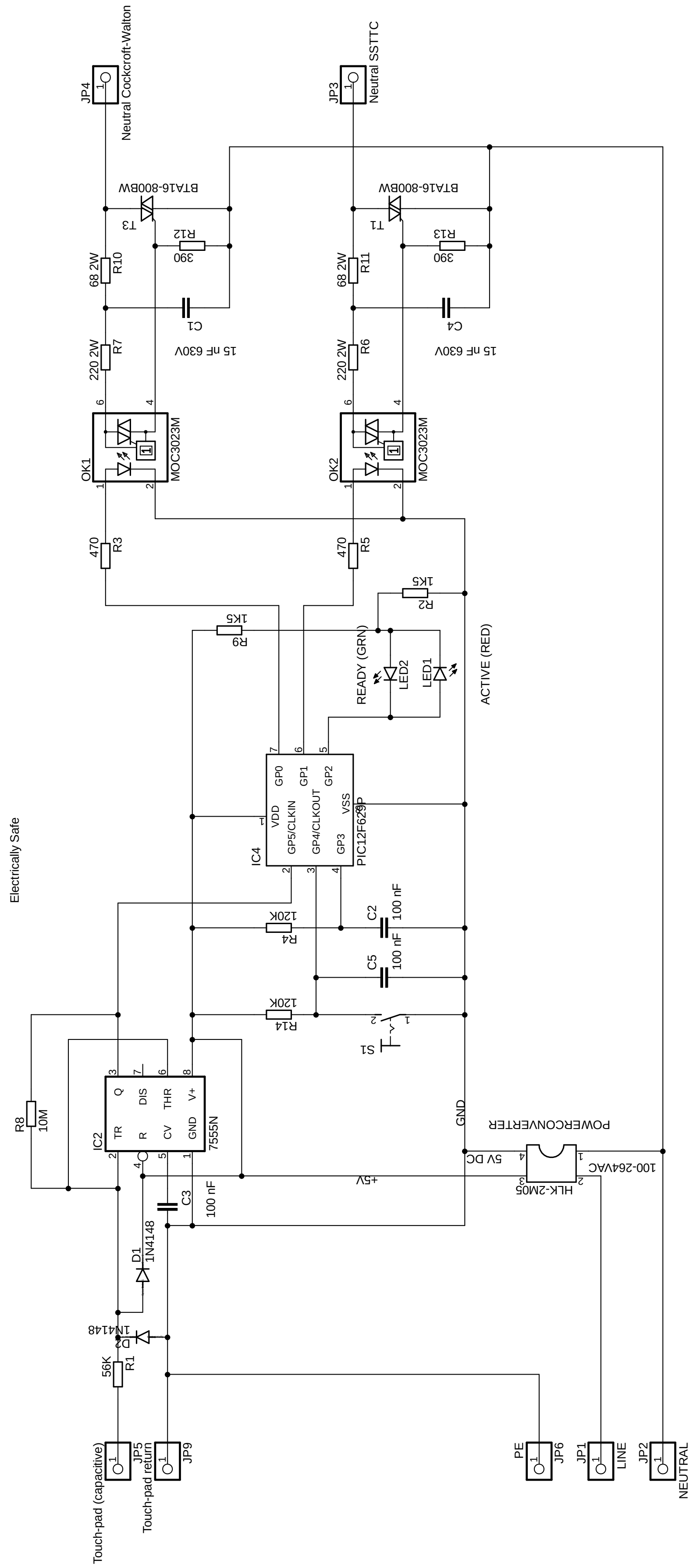

Fig. 28: Optically insulated dual mains controller for the SSTTC

9 Conclusions

A fully functional replica has been built of the original Twin Tesla Coil System originally designed and built by Prof. G.C. Damstra (1930–2012).

The operation of the system is largely reverse engineered using an available schematic diagram without component values. And from many available pictures of the original. The values of the storage capacitors for the explosive discharge are remembered from oral communication with Prof. Damstra.

A fundamental difference compared to the original is the active solid-state circuit that measures the replica's secondary coil's currents to drive the primary coils based on the Armstrong or Meißner generator principle.

The original had Tesla's traditional spark-gap primary resonator which had to be tuned to the secondary resonant frequency.

The replica's scale is 1:5. All relevant measures as well as instructions and schematic diagrams to build the scale model are provided in the text.

Another difference compared to the original is the addition of a PIC controlled triac power switch to operate the SSTTC by touch-control in a showcase.

The replica is not intended as a toy!

In addition to the relatively harmless high frequency –1 MHz– and high voltage –150 kV– low current sparks, the additional **2400 V DC** voltage between the two secondary top-loads contains a **capacitive energy of 34 J which can be lethal**.

Take appropriate precautions.

References

[1] G.C. Damstra and J.A.J. Pottings. "*Combined sources for lightning current tests*". In: Proc. 6th Int. Symp. on High Voltage Engineering New Orleans LA USA, Aug. 1989. URL: https://books.google.nl/books/about/Proceedings_of_the_6th_International_Sym.html?id=ZoHvHAAACAAJ&redir_esc=y.

[2] C. Gerekos. "The Tesla Coil". MA thesis. Université Libre de Bruxelles, 2012. URL: http://www.teslacoildesign.com/docs/TheTeslaCoil-Gerekos.pdf.

[3] Frits Buesink, Bart van Leersum, and Frank Leferink. "Reliable Systems Design using Current Boundaries". In: *IEEE EMC Magazine* 6.1 (May 2017), pp. 56–61. DOI: 10.1109/MEMC.2017.7931984.

[4] C. H. A. Keyer, F. J. K. Buesink, and F. B. J. Leferink. "Mains power synchronous conducted noise measurement in the 2 to 150 kHz band". In: *Proceedings of the 2016 International Symposium on Electromagnetic Compatibility (EMCEurope2016)*. Wroclaw, Poland: IEEE Electromagnetic Compatibility Society, Sept. 2016, pp. 865–869. DOI: 10.1109/EMCEurope.2016.7739266.