2. Functional Blocks of ESD Generator

With respect to the technical requirements for the ESD generator, it is divided into seven functional blocks as it is shown in Fig. 1. These blocks are:

(1) Power supply,
(2) User interface,
(3) Controller,
(4) High-voltage generator,
(5) Pulse shaper,
(6) Output switch, and
(7) Mechanical support.

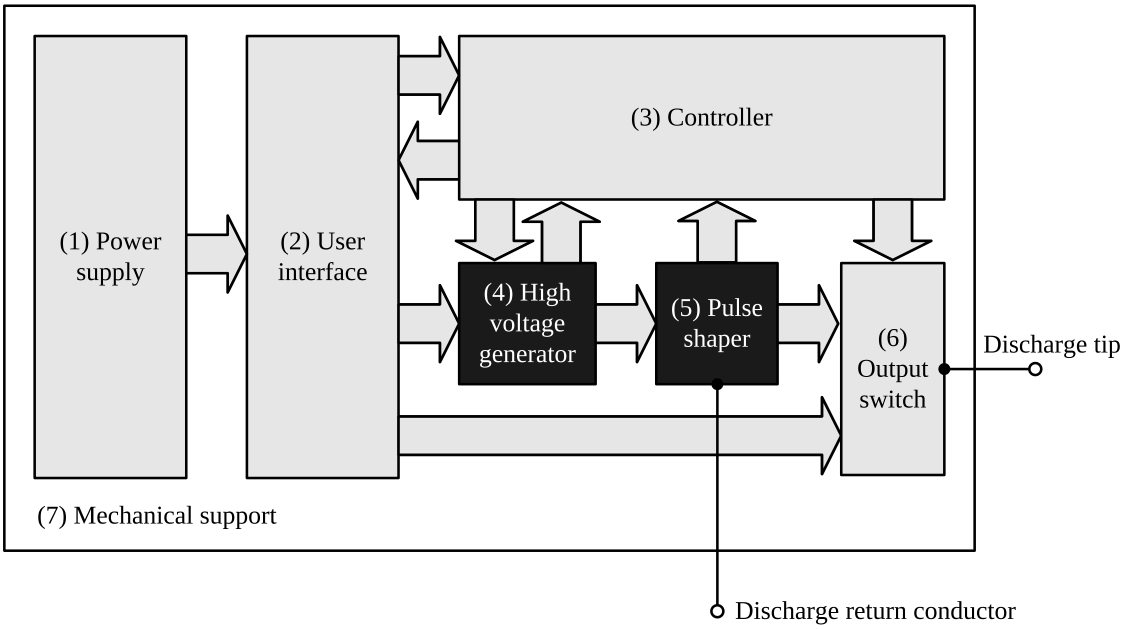

Figure 1. Functional blocks of ESD generator.

The roles for each of these functional blocks are outlined below. Note that the communication between different functional blocks is designated by arrows. The directions of the communication are shown in Fig. 1 so that the outline is general, i.e. some of the communications might be omitted in the final version.

Two functional blocks, namely (4) high-voltage generator and (5) pulse shaper are emphasized by dark color due to the fact that those blocks represent the core functionality of the ESD generator. All other blocks have supporting functions. Therefore, the focus of this document is primarily on technical possibilities and different topologies of electrical circuits for those two core functional blocks, for which schematics and topologies of considered alternatives are presented.

2.1. Power Supply

The role of the power supply is to provide electrical energy for the ESD generator, including all needed converters. The considered alternatives, including alternating current (AC) and direct current (DC), are given in Table I.

Table I. Considered alternatives for the power supply.

Solution	**Pros**	**Cons**	**Costs**
AC	– Energy is available as long as there is (public) power supply	– Safety in case of assembly and repair, – Power cord length limits the reach of ESD generator, – AC/DC converters are needed	– A socket on board of ESD and power cable: approximately 5 €
Battery Li-Ion 3.7 V 18650 2000 mAh	– Autonomous operation, – Charging with any mobile phone charger, – No health hazards during assembly and repair	– Limited energy, – DC/DC converters needed	5 € each
Battery Li-Ion 3.7 V 18650 2600 mAh	– Autonomous operation, – Widely available, –Charging with any mobile phone charger, – Best density of electrical energy in given volume and mass, – No health hazards during assembly and repair	– Limited energy, – DC/DC converters needed	6 € each
VARTA Ni-MH 8.4V, 200mAh	– Autonomous operation, – Widely available, – No health hazards during assembly and repair	– Very limited energy, – Specific charger needed, – DC/DC converters needed	10 € each
Accumulator battery 12 V 1.2 Ah – 18 Ah	– Autonomous operation, – Easy to buy, – No health hazards during assembly and repair	– Bulky, – Specific charger needed, – DC/DC converters needed	10 € – 40 € each
Accumulator battery 6 V 4.5 Ah – 12 Ah	– Autonomous operation, – Available on the market, – No health hazards during assembly and repair	– Bulky, – Specific charger needed, – DC/DC converters needed	10 € – 15 € each
AAA batteries 1.2 V – 1.5 V (Rechargeable Ni-Mh)	– Autonomous operation – Widely available, – No health hazards during assembly and repair	– Specific charger needed, – Low energy per battery (up to 1.8 Whrs), – DC/DC converters needed	0.5 € each (approximately 5 needed at the same time)
AA batteries (Rechargeable Ni-Mh)	– Autonomous operation, – Widely available, – Smaller than most others, – No health hazards during assembly and repair	– Specific charger needed, – Medium energy per battery (up to 5 Whrs), – DC/DC converters needed	0.5 € each (approximately 5 needed at the same time)

2.2. User Interface

The role of the user interface is to allow the user to operate the ESD generator. More specifically, the following operations are required

(1) turn on/off,
(2) select the voltage level (both in fine step of 100 V and coarse step of 1 kV),
(3) charge the ESD generator before discharge (if needed),
(4) present the current status of the ESD generator on LCD,
(5) change of the pulse polarity (either manual or automatic),
(6) change the pulse repetition frequency,
(7) charging of the battery (if a battery is used),
(8) provide the battery status (if a battery is used),
(9) etc.

The switches, push (momentary) buttons, rotary decoders, LCDs, etc., must be mechanically robust and all the used components should be as immune as possible to ESD.

2.3. Controller

The role of the controller is to orchestrate all operations of the ESD generator. Based on selections from the user, the controller should drive the high-voltage generator, the output switch, and provide signals for LCD. The selection of the controller will be done after the core functional blocks have been defined. The controller should be as immune as possible to ESD.

2.4. High-voltage Generator

The role of the high-voltage generator (HVG) is to provide a high DC voltage in the range up to $U_{\max} = 30\,\mathrm{kV}$. This generator should provide only low current, as the output of HVG is intended to be connected to a shaper that can be approximated with a $C = 150\,\mathrm{pF}$ capacitor. The maximal energy provided at the output should be $W_{\mathrm{e}} = \frac{1}{2} C U_{\max}^2 = 67.5\,\mathrm{mJ}$. The generator should be able to charge the pulse shaper up to 20 times per second (i.e., at 20 Hz repetition rate; equivalent to 50 ms charging time).

We considered six different topologies of electrical circuits as possible solutions or partial solutions for the HVG. Most of the circuits are analyzed in free software LTspice [1].

Note that the most of the reviewed topologies need inductive transformer either implicitly or explicitly. This is due to the fact that the high voltage is needed at the output and that stepping-up of the voltage is needed. Therefore, multiple choices for transformers must be considered for each of those topologies.

2.4.1. Cascade for Voltage Multiplication

The first considered topology is a cascade of capacitors and diodes that is often used to produce a high-voltage DC output from a given AC input. This circuit is also referred to as a Greinacher cascade, a Cockcroft-Walton multiplier, or a Villard cascade [2]. The topology of this circuit, with a single cascade, is shown in Fig. 2. The output voltage is $V_{\mathrm{out}} \le N V_{\max}$, where N is the total number of capacitors in the cascade and $V_{\max}$ is the amplitude of the AC voltage at the input of the cascade. An example of the output voltage as a function of time is shown in Fig. 3.

Instead of a single cascade, two cascades in parallel with diodes in the opposite directions can be used to produce a two times larger output. The topology of this circuit is shown in Fig. 4 and its output voltage is shown in Fig. 5. The double cascade offers the possibility to have both a positive and a negative output voltage by simple interchange of output terminals.

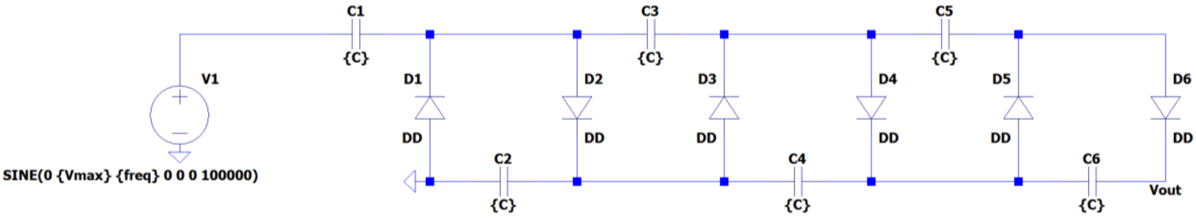

Figure 2. Topology of cascade of capacitors and diodes for voltage multiplication.

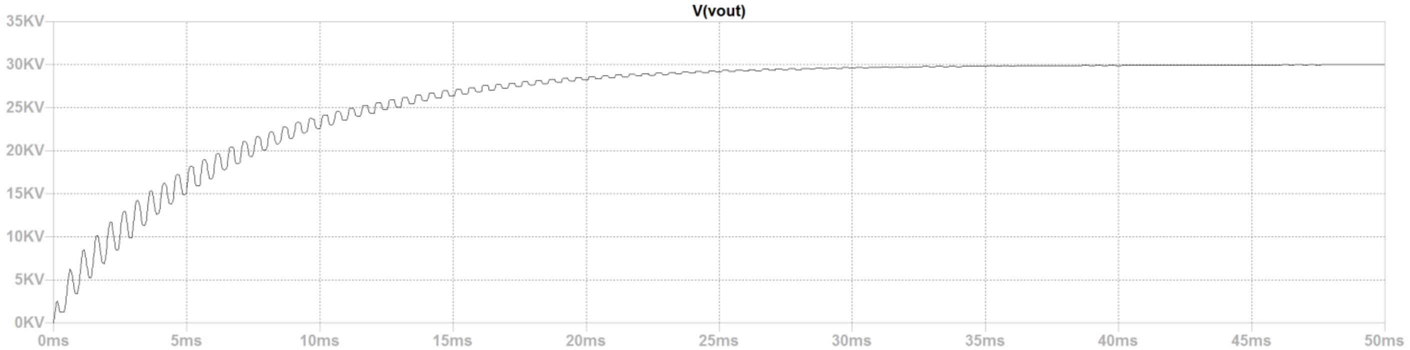

Figure 3. Illustration of the output voltage of the cascade for voltage multiplication shown in Fig. 2

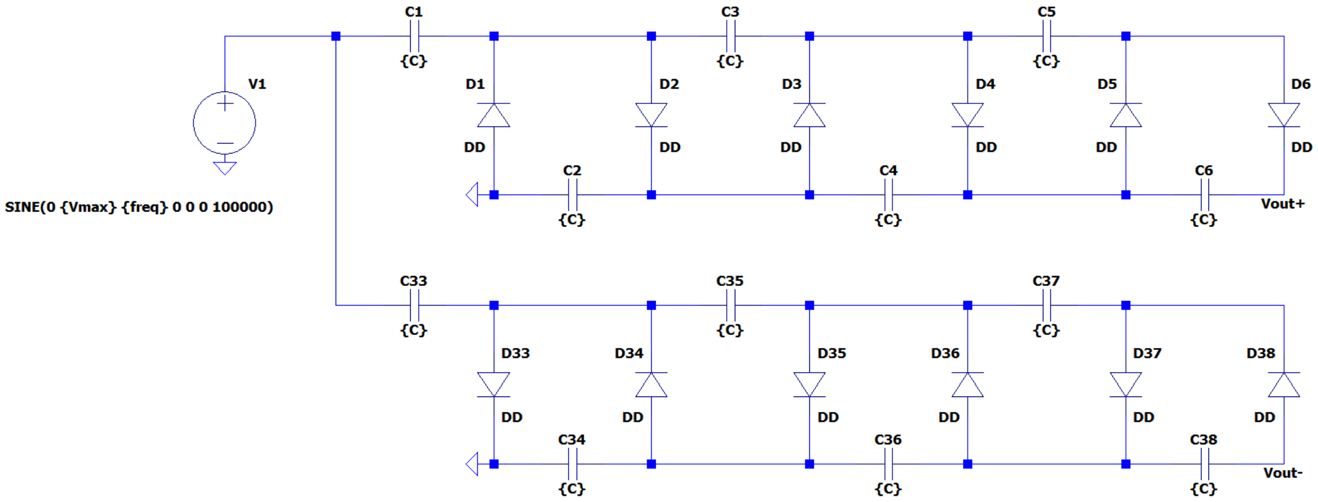

Figure 4. Double cascade for voltage multiplication.

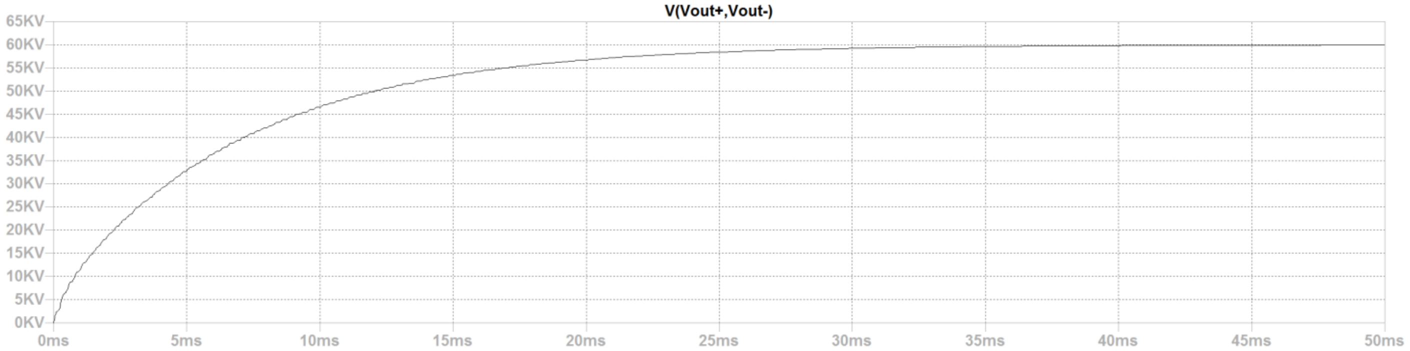

Figure 5. Illustration of the output voltage for double cascade for voltage multiplication shown in Fig. 4.

In practice, the capacitors in the cascade must be rated for a voltage higher than $2V_{\text{max}}$. The diodes are never ideal. Their forward voltage reduces the output voltage (however, this effect is negligible for the ESD generator), while their reverse leakage currents discharge the capacitors over time. There is an optimal capacitance that depends on the frequency of the excitation generator, the generator maximal output current, and the used diodes if the desired output voltage should be produced in a given time. Finally, the equivalent load seen from the AC generator into the cascade changes over time: at the beginning, the capacitors are empty, while after some time they become practically fully charged. The AC generator at the input of the cascade should typically have the amplitude of the order of kV. Hence, it must be considered carefully and most likely is based on an inductive transformer.

2.4.2. Marx Generator

Another classic option for voltage multiplication is the so-called Marx generator [3]. The topology of this circuit is shown in Fig. 6. The basic idea is to use a DC generator at the input, which charges capacitors in parallel. Once the capacitors are charged, the discharge is initiated by closing all the switches in the circuit. In the LTspice schematic, the operation of the switch is controlled by a pulse generator (V2). The typical output voltage is shown in Fig. 7. In practice, the switches are spark gaps, either in the air or in a pressurized gas.

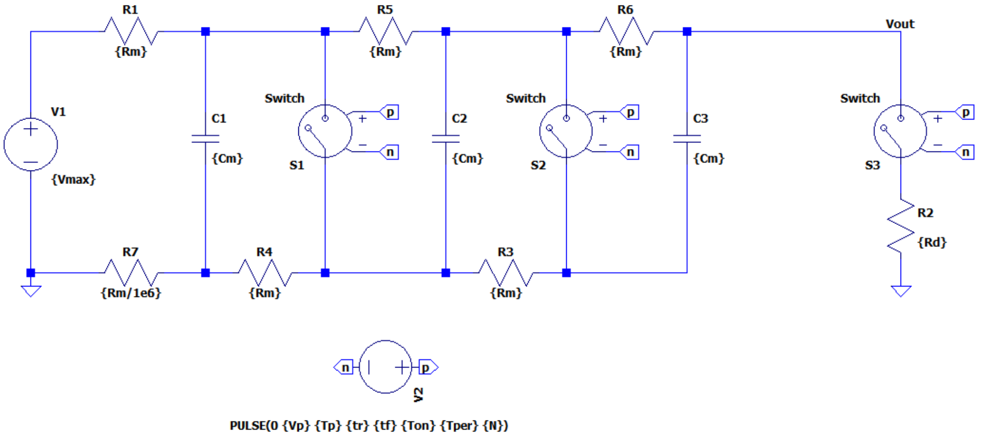

Figure 6. Topology of a Marx generator.

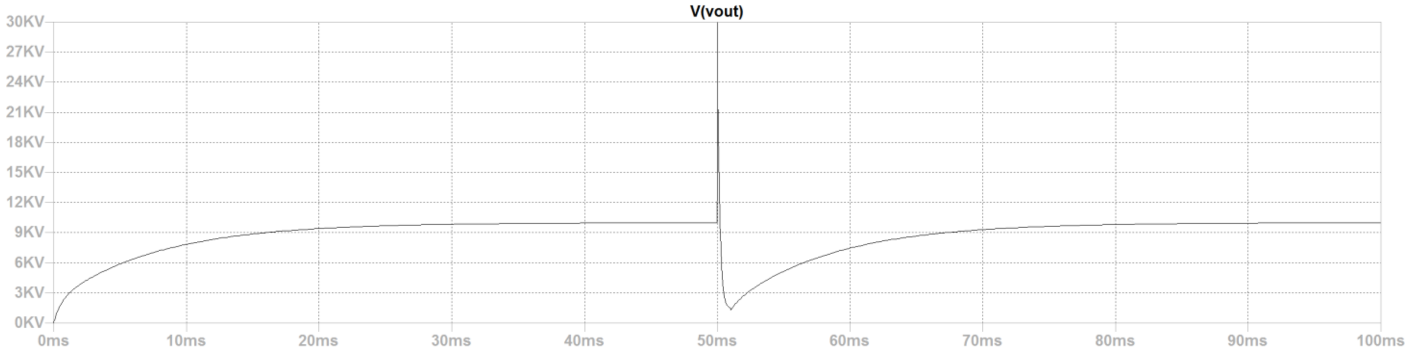

Figure 7. Typical output voltage for Max generator shown in Fig. 6.

2.4.3. Resonance Energy Transfer

This is one of the simplest circuits that can be used to charge the output capacitor with a high voltage. The topology is shown if Fig 8. The circuit consists of a DC-voltage source (V1), an inductor (L1; coil, choke), a fast, high-voltage switch (VSW; e.g., a vacuum relay), a rectifier diode (D1), and the output capacitor (Cout). Coil losses are modeled by R1. In the LTspice schematic, the operation of the switch is controlled by a pulse generator (V2). In order to start the charging cycle, the switch closes. The current of the coil (IL1, whose reference direction is downwards) increases until the switch opens. At that moment, an induced electromotive appears in the coil (the positive terminal of the coil voltage is the lower one). The diode starts conducting and L1 and Cout create a resonant circuit. The magnetic energy stored in the coil initiates oscillations in this resonant circuit and practically the complete energy of the coil is quickly transferred to Cout, within one quarter of the cycle, so that the output voltage V(Output) increases abruptly. However, the oscillations cannot continue thereafter because the diode does not allow the current to flow in the opposite direction. Hence, Cout remains charged. An illustration of the output of this circuit is shown in Fig. 9. The weak point of this circuit is the requirement for a robust switch, which can withstand high current and high voltage.

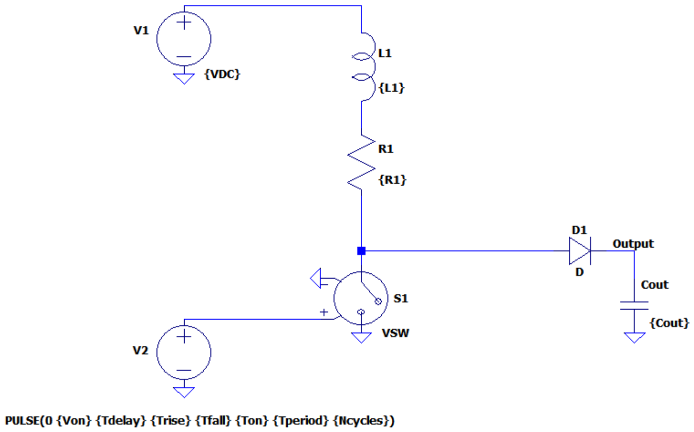

Figure 8. Topology for resonance energy transfer.

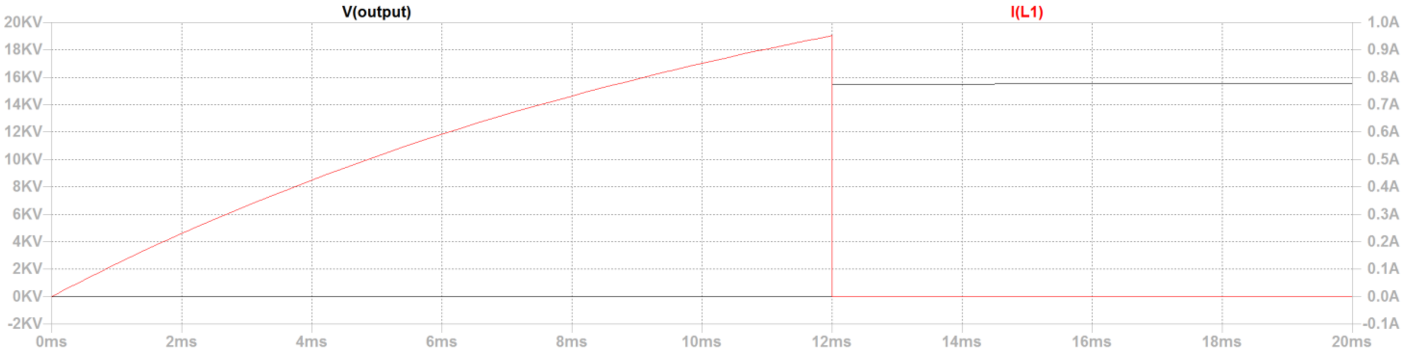

Figure 9. Illustration of the voltage output for the resonance energy transfer.

2.4.4. Audio System with Cascade for Voltage Multiplication

The topology of this circuit is shown in Fig. 10. The energy required to charge the output capacitor is delivered by an audio amplifier (Voltage_source), which is excited by a sinusoidal signal. The signal is brought to the primary of a step-up audio transformer through a matching and conditioning network that consists of three capacitors (Cl, Cp, and Cs). Losses in the transformer are modeled by the resistors R1 and R2. At the secondary of the transformer, high voltage appears. The secondary energizes a cascade for voltage multiplication, which further increases the voltage up to the level required to properly charge the output capacitor. An illustration of the output is shown in Fig. 11.

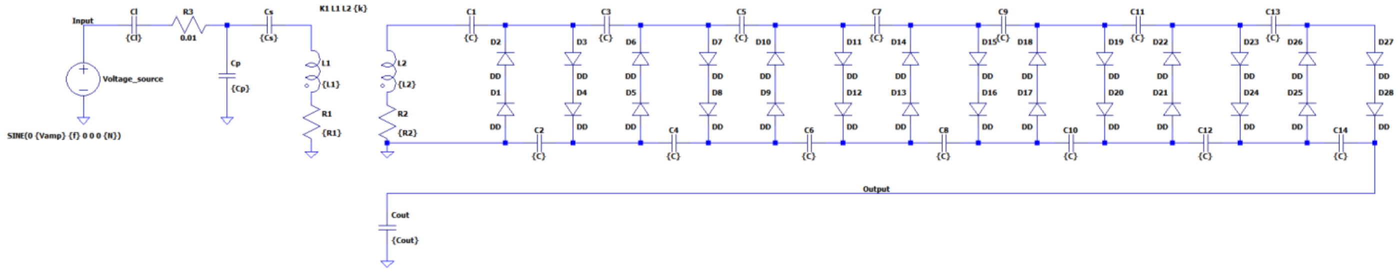

Figure 10. Topology of audio system with cascade for voltage multiplication.

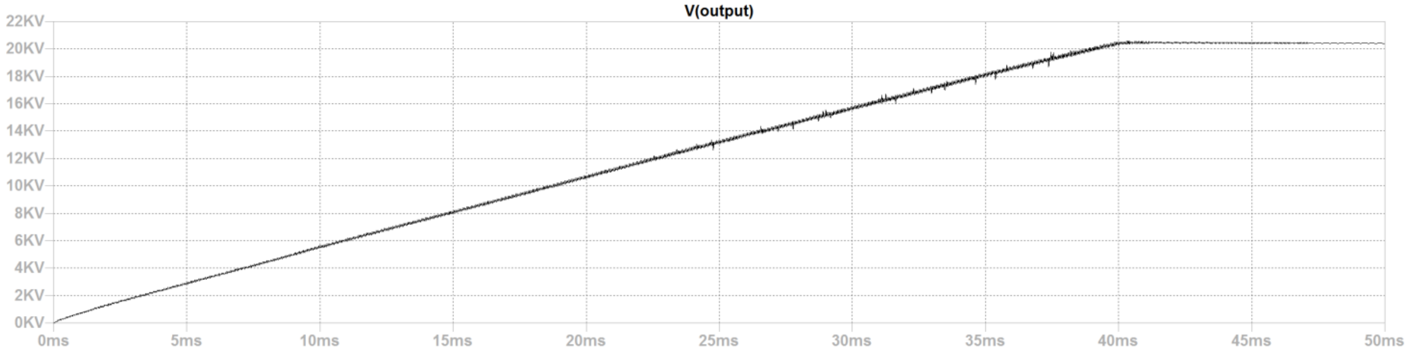

Figure 11. Illustration of the voltage output of audio system with cascade for voltage multiplication.

2.4.5. Flyback Converter with Cascade for Voltage Multiplication

The topology of the circuit is shown in Fig. 12. The flyback converter with voltage multiplication consists of a DC voltage source VCC, voltage pulse generator (Controller) that drives a transistor that acts as a switch, high-voltage transformer and a cascade for voltage multiplication. When the switch (transistor) is closed, the current rises in the primary of the transformer. When the switch opens, the magnetic energy stored in the primary coil is transferred to the secondary coil and further to its load [4]. An illustration of the output is shown in Fig. 13. Note that practically the same topology with a (controlled) switch and a high-voltage transformer is used in induction coil systems for internal-combustion engines.

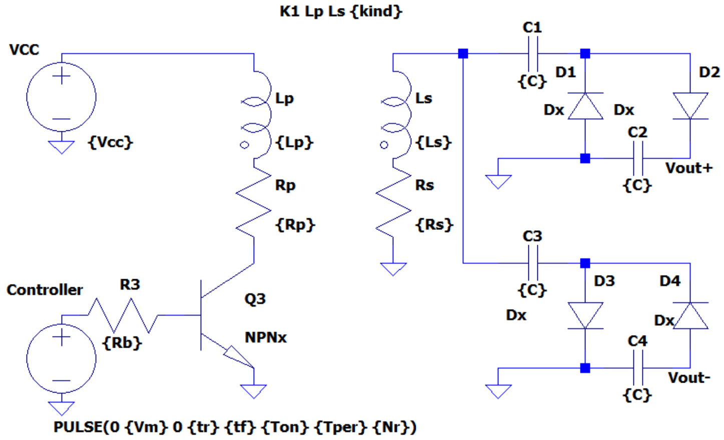

Figure 12. Flyback topology with two cascades for voltage multiplication.

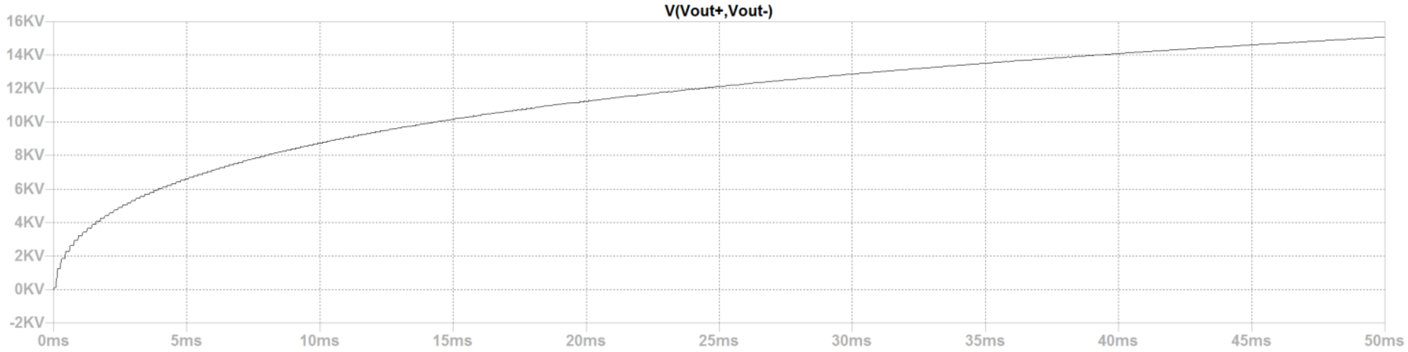

Figure 13. Illustration of the output voltage of a flyback with cascades for voltage multiplication.

2.4.6. Electronic Fluorescent Lamp Ballasts

Yet another possibility for generation of high voltage is electronic ballasts for (compact) fluorescent lamps. While there are many implementations of those ballasts, they can be classified into three categories: (a) voltage-fed half-bridge quasi-resonant lamp ballast, (b) current-fed half-bridge resonant lamp ballast, and (c) push-pull resonant ballast [5]. Those three topologies are shown in Figs. 14, 15, and 16, respectively. Out of those three topologies, only the push-pull ballast can withstand high-voltage at the open ends. Hence it is combined with controllers and a cascade for consideration for our HVG. The topology of such a circuit is shown in Fig. 17, while an illustration of the output voltage is shown in Fig. 18. The idea is that only one of two transistors (switches) is closed at a time, while the other is open, so that there is alternate voltage at the output of the transformer. This output is then connected to a cascade for voltage multiplication, thus generating the high-voltage output.

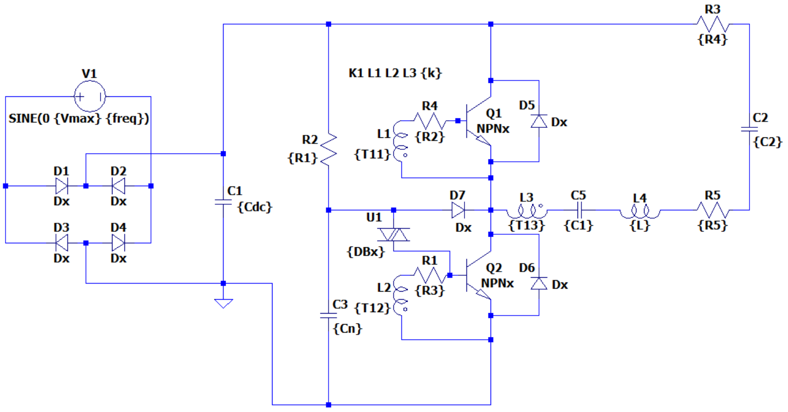

Figure 14. Topology of voltage-fed half-bridge quasi-resonant lamp ballast.

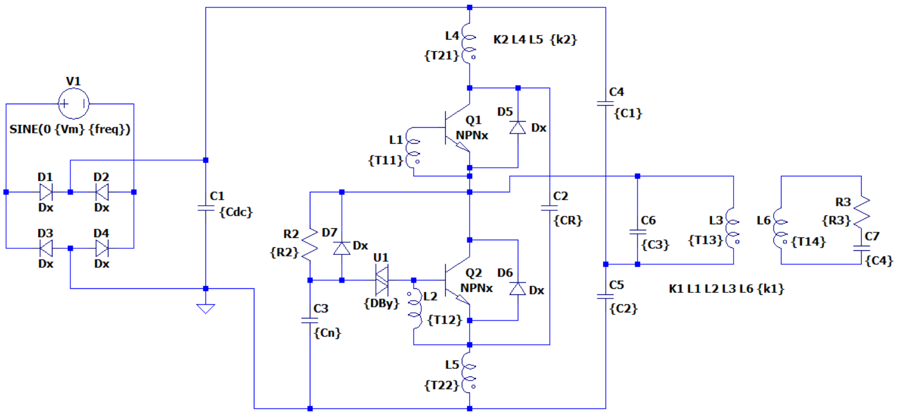

Figure 15. Topology of current-fed half-bridge resonant lamp ballast.

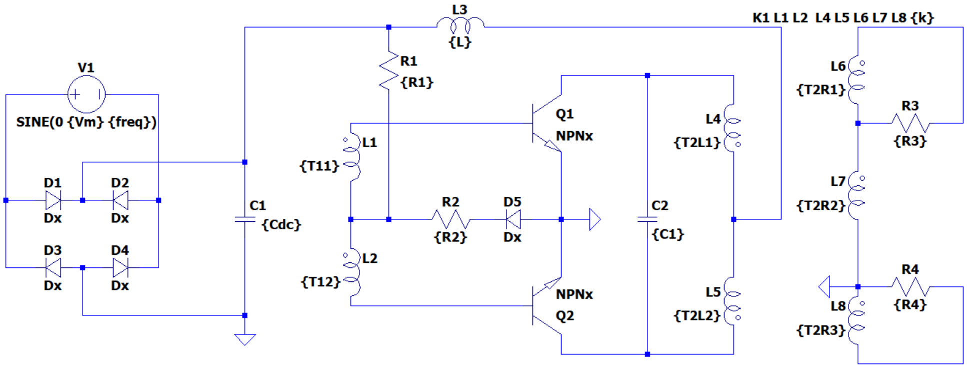

Figure 16. Topology of push-pull resonant ballast.

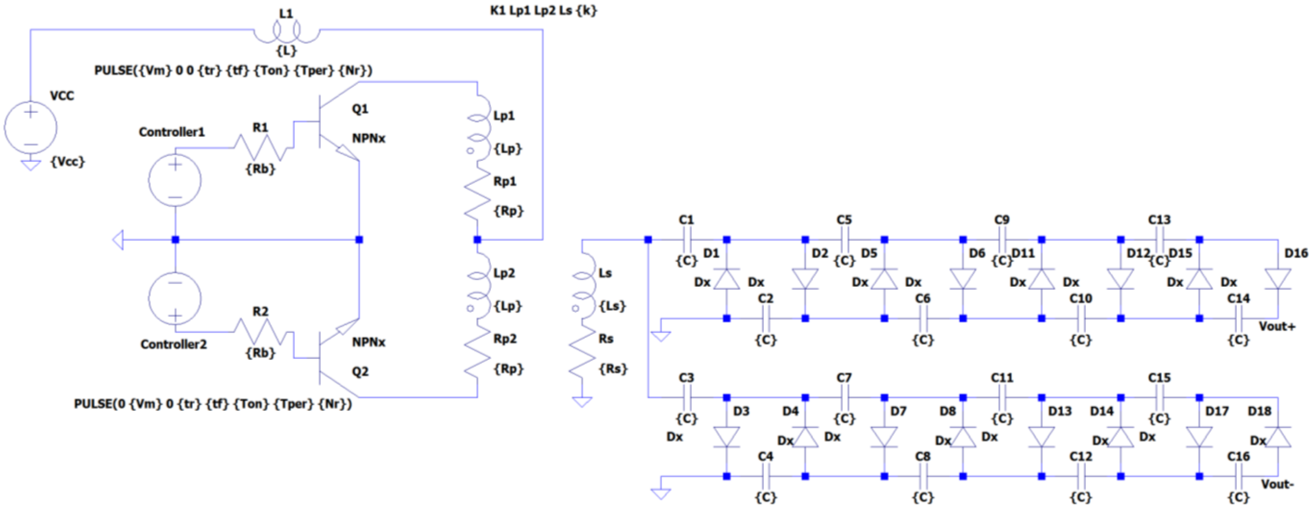

Figure 17. Topology of push-pull circuit with transformer and two cascades for voltage multiplication.

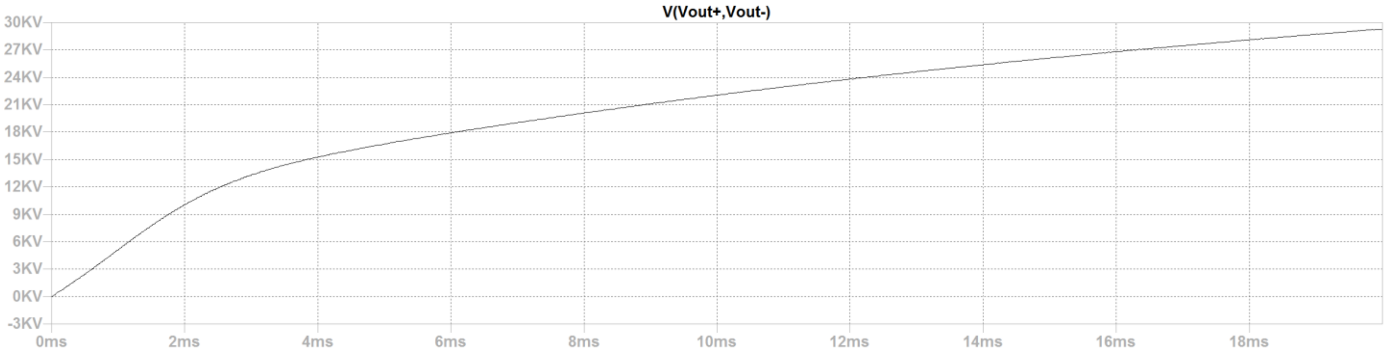

Figure 18. Illustration of the high-voltage output of push-pull topology.

2.5. Pulse Shaper

The role of this circuit is to shape the high-voltage pulse so that the output current is as close as possible to the predefined current pulse in the IEC-61000-4-2. Multiple topologies for pulse shaper are considered. All of them consider a high-voltage input obtained from HVG. For the following illustrations of the output current we assumed 4 kV discharge level (modeled as the input voltage of the shaper, Vmax).

2.5.1. Pulse Shaper #1

The first considered shaper is in the form of a ladder network with two cells, shown in Fig. 19. In Fig. 20 the standard current pulse is compared with the output current of the pulse shaper #1.

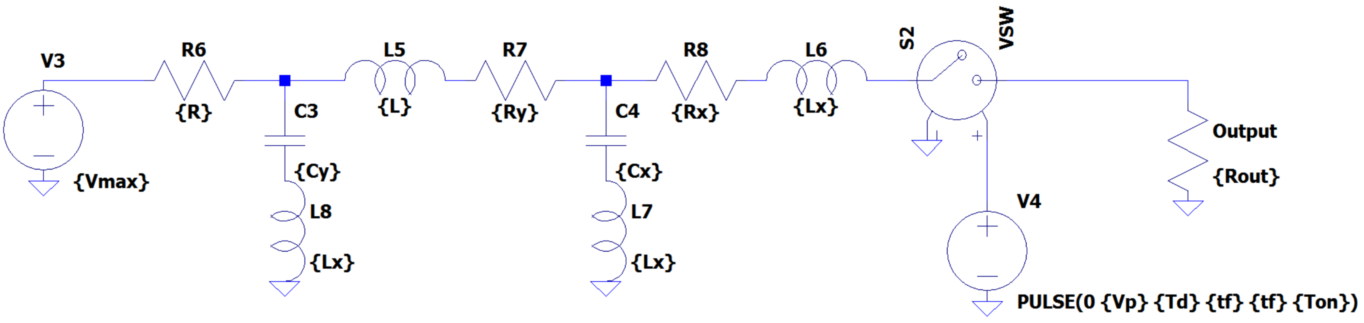

Figure 19. Topology of ladder network with two cells made of capacitors, resistors and inductors (pulse shaper #1).

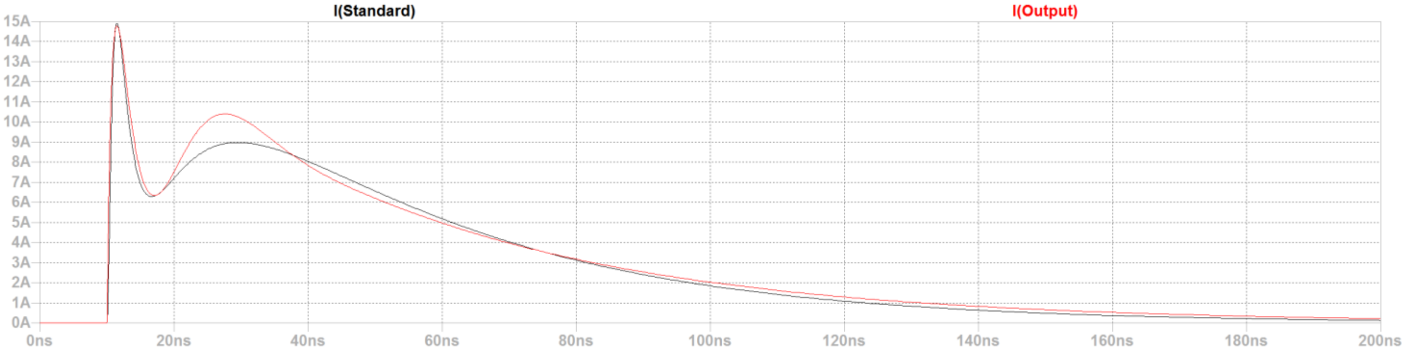

Figure 20. Comparison of standardized output current and current obtained from pulse shaper #1.

2.5.2. Pulse Shaper #2

The second considered shaper is in the form of a ladder network with three cells from [6], shown in Fig. 21. Its calculated output current is compared to the standardized one in Fig. 22. Note that if values for parameters are taken from [6], the peak of the output current is approximately three times larger than the standard peak value.

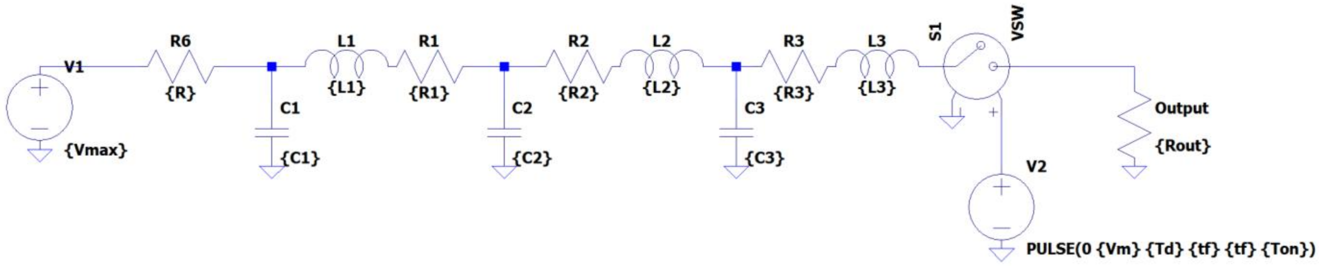

Figure 21. Topology of three-cell ladder-network shaper (pulse shaper #2).

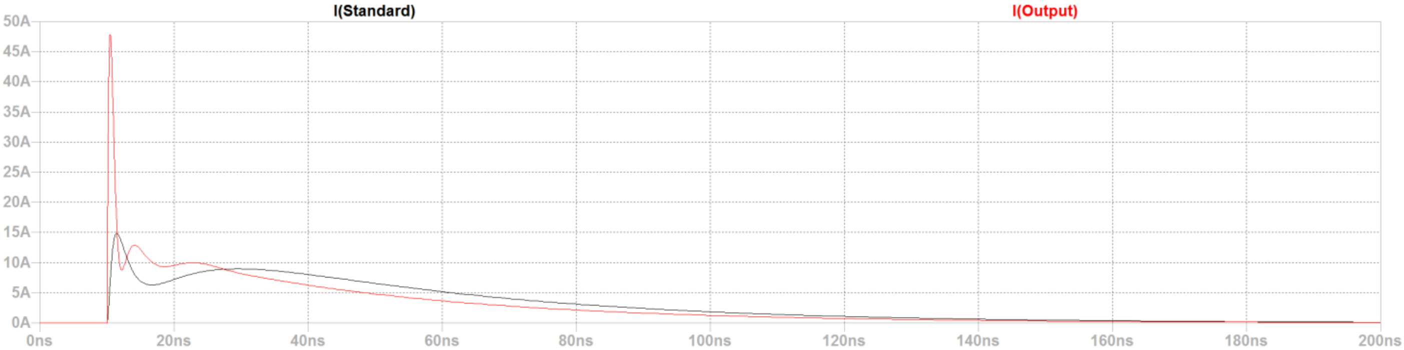

Figure 22. Comparison of standardized output current and current obtained from pulse shaper #2.

2.5.3. Pulse Shaper #3

The third considered topology for the shaper is shown in Fig. 23, while an illustration of the output current is shown in Fig. 24 [7].

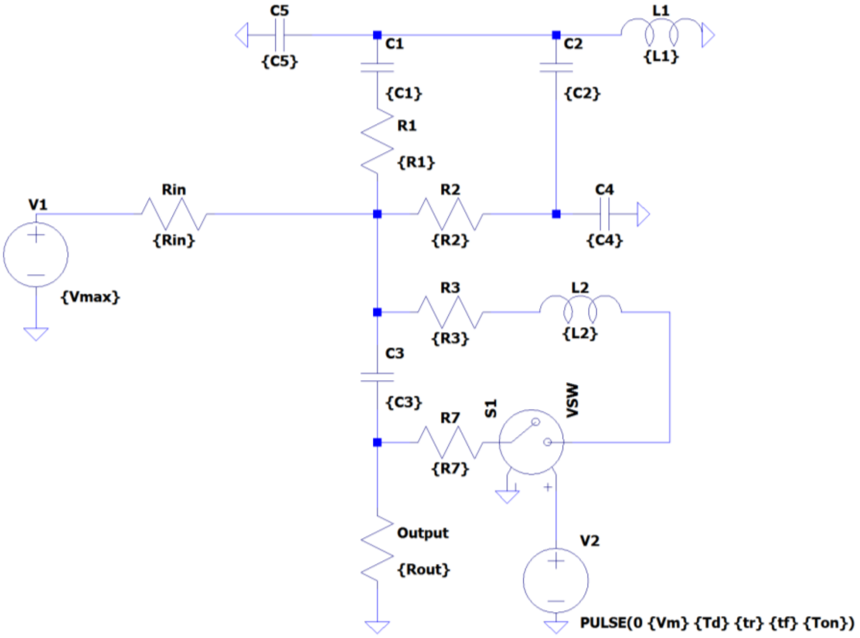

Figure 23. Topology of shaper obtained by comparison with finite-difference modeling (pulse shaper #3).

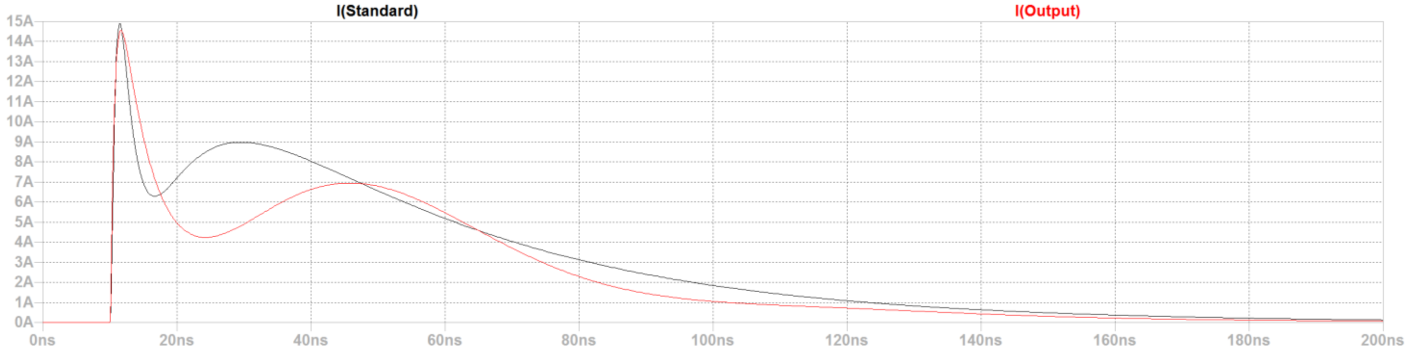

Figure 24. Comparison of standardized output current and current obtained from pulse shaper #3.

2.5.4. Pulse Shaper #4

The fourth considered topology for the shaper includes a transmission line [8], as it is shown in Fig. 25. Its output current is shown in Fig. 26.

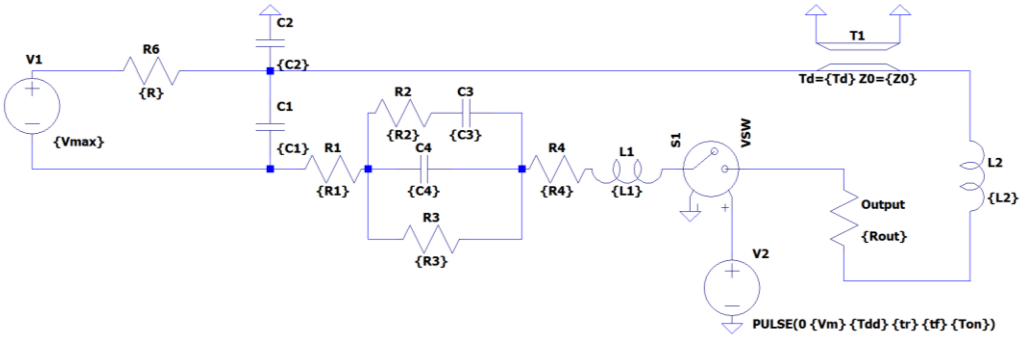

Figure 25. Topology of shaper with a transmission line (pulse shaper #4).

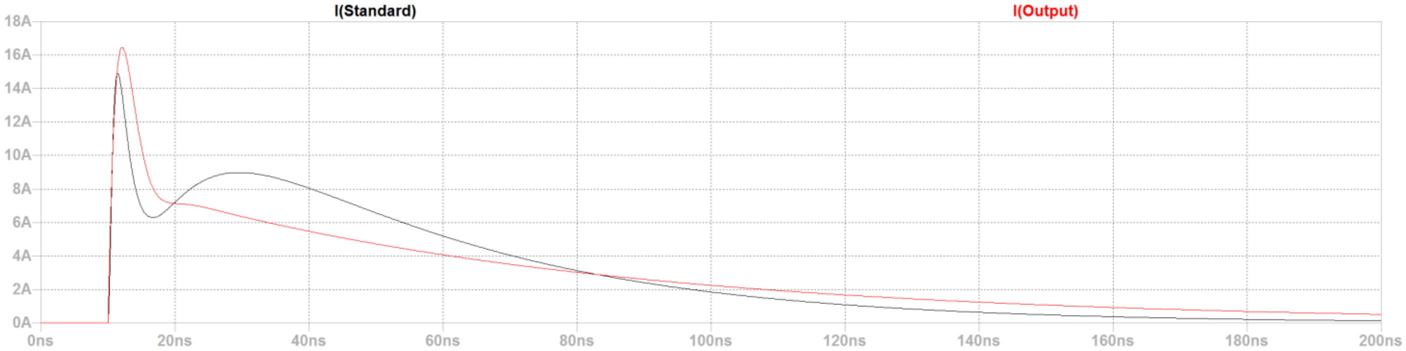

Figure 26. Comparison of standardized output current and current obtained from pulse shaper #4.

2.5.5. Pulse Shaper #5

The fifth considered topology of the shaper is obtained from 3D modeling [9]. The topology of the circuit is shown in Fig. 27, while the output current is shown in Fig. 28.

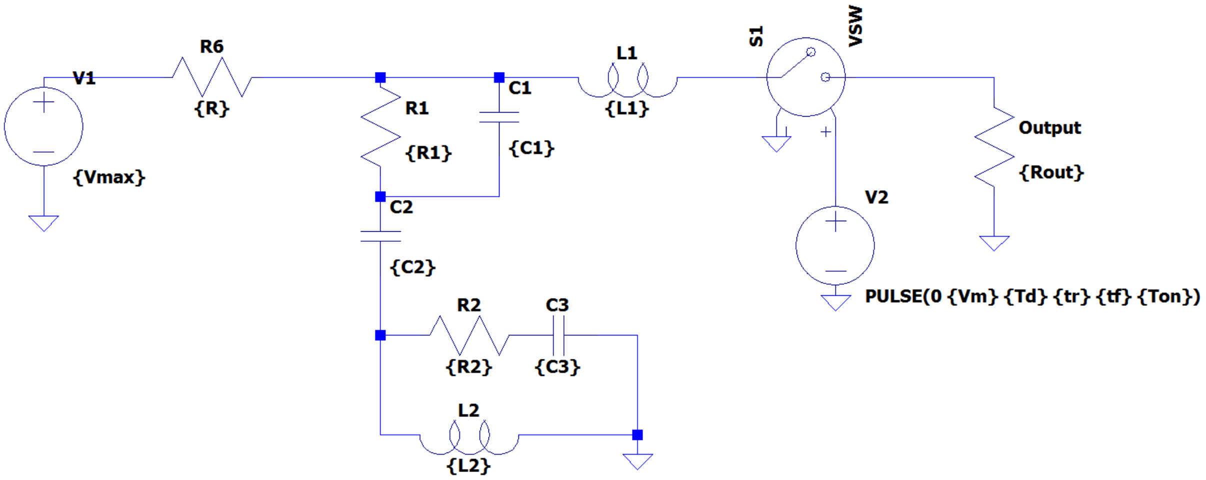

Figure 27. Topology of shaper obtained from 3D modeling (pulse shaper #5).

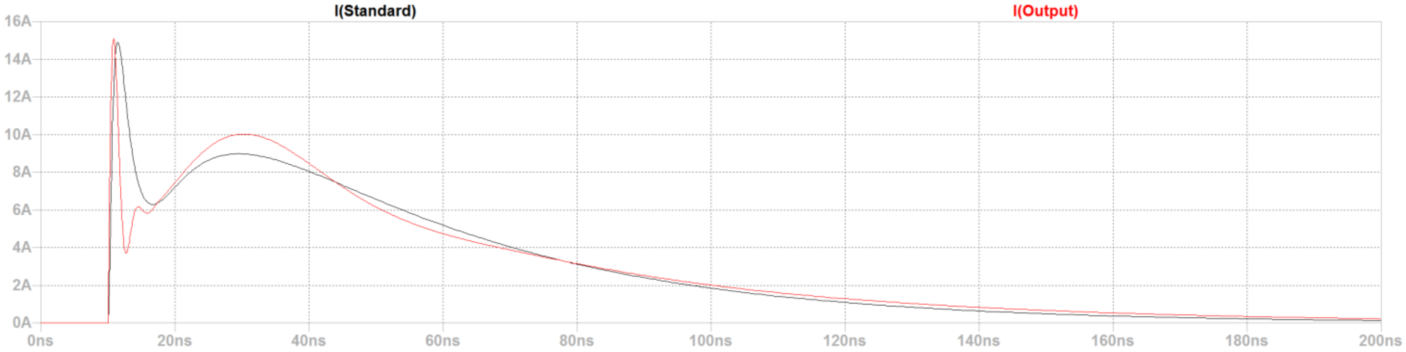

Figure 28. Comparison of standardized output current and current obtained from pulse shaper #5.

2.5.6. Pulse Shaper #6

The sixth considered topology for the shaper is shown in Fig. 29. An illustration of the output current is shown in Fig. 30. Unlike the previous shapers, this one inverts the output current, i.e., for the shown results, the input voltage is of the opposite polarity.

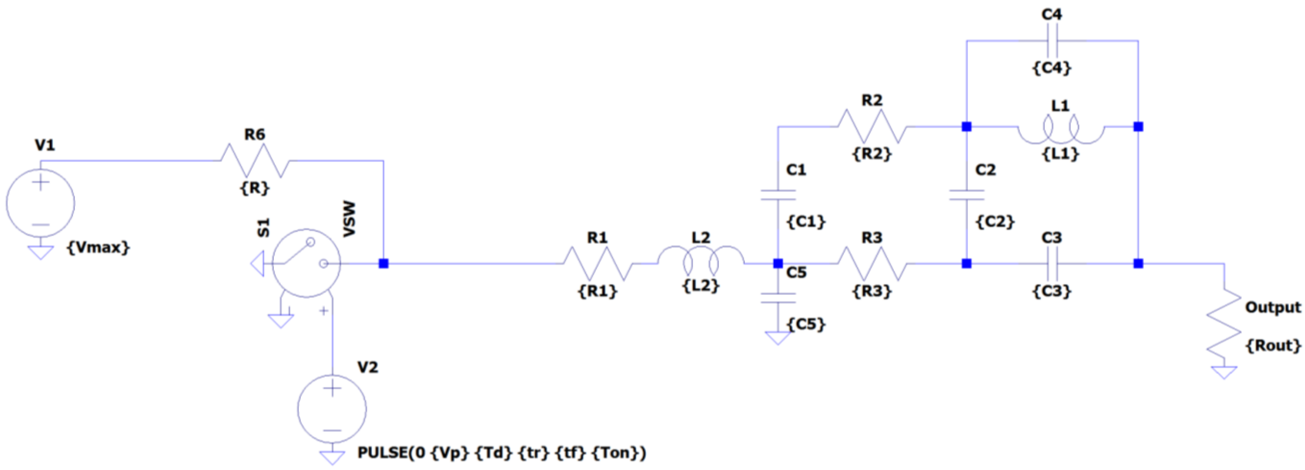

Figure 29. Topology of inverting shaper (pulse shaper #6).

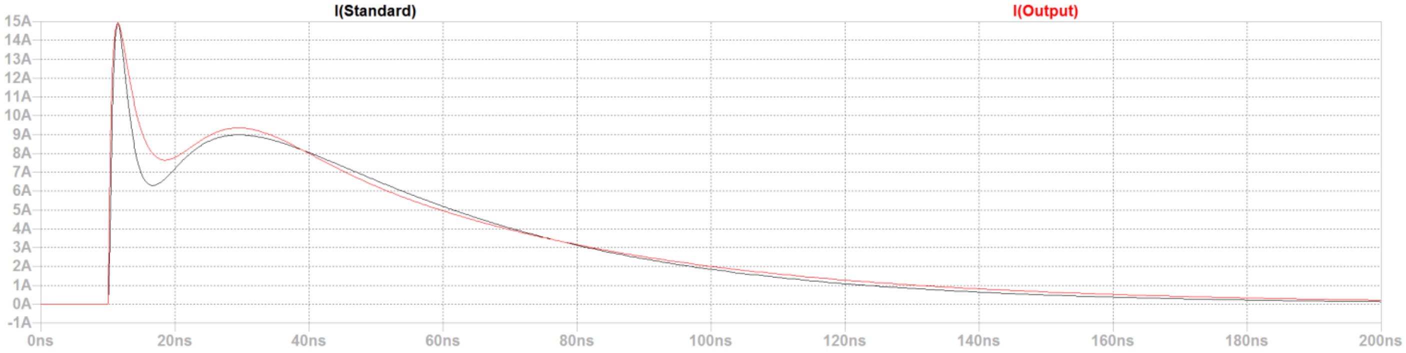

Figure 30. Comparison of standardized output current and current obtained from pulse shaper #6.

2.5.7. Pulse shaper #7

The seventh considered topology for the shaper is shown in Fig. 31. It consists of two series RLC branches which are in parallel with one another. Its output current is shown in Fig. 32.

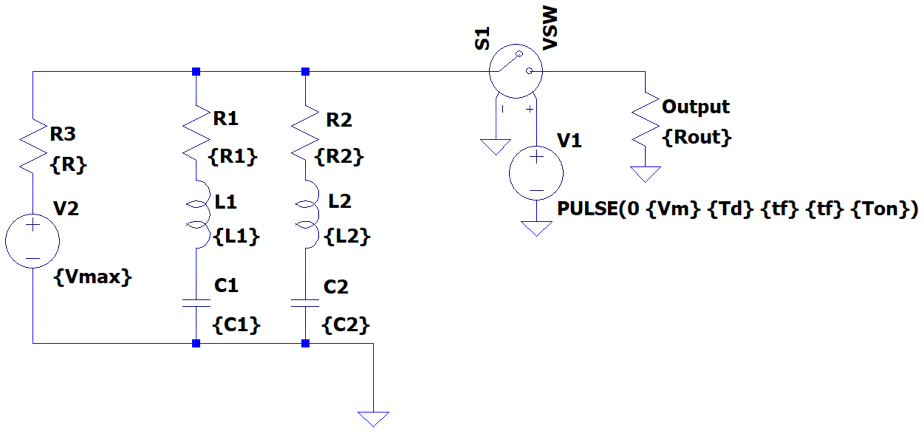

Figure 31. Topology of pulse shaper #7.

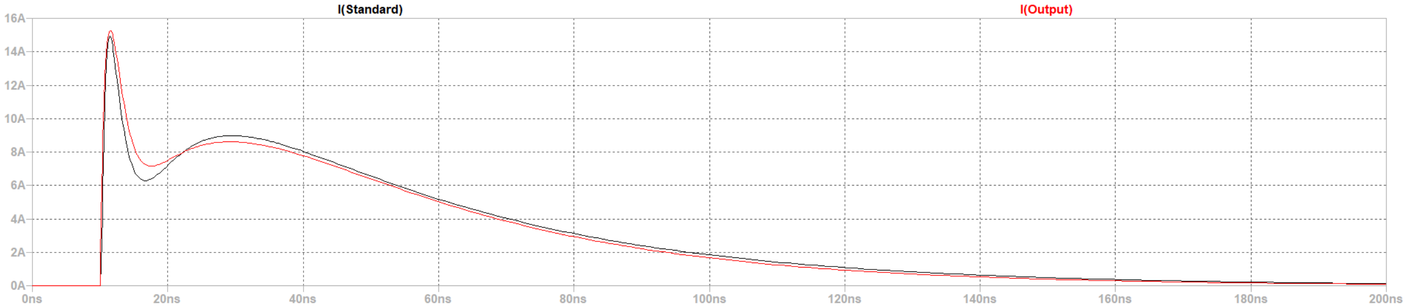

Figure 32. Comparison of standardized output current and current obtained from pulse shaper #7.

2.6. Output Switch

The role of the output switch is to initiate discharge for the contact discharge of the ESD generator. The switch should be able to withstand connecting and disconnecting the voltage up to at least 8 kV due to the technical requirements for the contact discharge. The output switch most likely will be circumvented in the case of air discharge of the ESD generator.

2.7. Mechanical Support

Mechanical support consists of the ESD generator enclosure, the grip (if needed), interchangeable discharge tips, connector for the discharge return conductor, etc. Its design will be considered once all the other functional blocks of the ESD generator are defined.

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Revision history

Version	Date	Author(s)	Description
1.0	07/07/2024	D.O., A.Dj., J.D., D.N., A.K.	Initial release.
1.1	26/07/2024	A.K., D.O.	Added shaper #7, altered Figs. 14, 15 and 16.
1.2	12/10/2024	D.O.	New chapter numbering due to Read the Docs migration.