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Simulation and Experimental Development of 100 kV Impulse Voltage Generator

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Abstract – The disruptive effects on energy transmission and distribution systems are caused by transient voltage increases that affect the grid in natural or indirect ways. The most important of these are lightning impulse voltages that occur in nature and switching impulse voltages caused by opening and closing operations in the grid. The design of power systems is done to minimize the effects of these types of transient voltages. However, unpredictable excessive voltage magnitudes or insulation weaknesses of equipment in the system can still cause serious damage to the entire system. Therefore, the design of equipment used in power systems is carried out in accordance with the concept and standards of insulation coordination, and the equipment produced is tested in laboratory conditions according to the excessive voltages that can occur in the grid before being used in the grid. In this study, the lightning impulse generator located in High Voltage Laboratory at Yildiz Technical University has been reviewed and developed for its intended use. Changes have been made in the structure of the impulse voltage generator so that 100 kV lightning impulse generator can apply lightning impulse voltage consecutively every 15 seconds. The values of the required circuit elements were recalculated and tested with a simulation study using MATLAB/Simulink software program. By creating circuit parameters whose suitability was verified by calculated and simulation studies, a lightning impulse generator was developed in the laboratory environment. The modified impulse voltage generator was experimentally tested on different samples. As a result, the theoretical findings obtained from the simulation study were also experimentally confirmed.

Keywords – Circuit Design, High Voltage Tests, Impulse Voltage Generator, Modelling

I. INTRODUCTION

The advancement of technology, the power system has become more complex, which in turn makes the insulation coordination more challenging. The insulation coordination is the process of selecting the insulation levels and the protective devices to ensure that the power system operates without any insulation failure under the expected overvoltage conditions. The coordination aims to minimize the cost of the insulation system while maintaining the system's reliability.

Insulation coordination studies involve determining the overvoltage stresses that a power system may experience, selecting the insulation levels for the equipment based on the expected stresses, and designing the protective devices to limit the overvoltage stresses below the insulation strength of the equipment [1]. The equipment's insulation levels are typically designed to withstand the voltage stresses that the equipment may experience during its operational life. However, certain events, such as lightning strikes or switching surges, can generate overvoltages that exceed the equipment's insulation level, leading to insulation failure [2].

Various international standards and conditions have been defined for the production and measurement of impulse voltages in laboratory environments [3–8]. Insulation tests of electromechanical products currently being produced require the measurement and testing of multiple parameters under not only standard waveform lightning and switching impulse voltages, but also under combined tests, as specified in the IEC 60060-1:2010 standard [5]. High impulse voltages are produced by special circuits known as Marx generators, which were developed by Erwin Otto Marx in 1924 as a multiple impulse voltage generator based on the single impulse voltage generator circuit developed by Charles P. Steinmetz and used in today's Marx generators [9–11]. In addition to standard lightning and switching impulse generators, these basic principle circuits are also used to produce very fast pulses with rise times of 100 ns or less, especially in insulator technology and military equipment testing [12–14].

This study aimed to develop a lightning impulse generator that is suitable for use in the High Voltage Laboratory of Yildiz Technical University. Changes were made to the structure of the impulse voltage generator to allow the application of lightning impulse voltage consecutively every 15 seconds. The values of the required circuit components were theoretically recalculated and the layout of the impulse generator was reviewed. A simulation study was conducted using MATLAB/Simulink software to evaluate the theoretical findings. The operation of the generator was analyzed under both unloaded and loaded conditions. The circuit parameters that were confirmed to be suitable for use as a result of the theoretical and simulation studies were applied experimentally on a lightning impulse generator in the laboratory. The developed impulse voltage generator was tested experimentally on different test samples. As a result, the theoretical findings obtained through simulation were experimentally verified, and the development of lightning impulse generator was completed.

II. Materials and Method

In high-voltage experiments conducted for fundamental research on the stresses and breakdown events in internal and external overvoltages, impulse voltages are required. Impulse voltages are generated during the discharge of high-voltage capacitors through resistors and capacitors with multiple series-parallel connections. In high-voltage technology, an impulse voltage is understood to be a DC voltage pulse with a positive or negative polarity [13].

The shape and duration of an impulse voltage depend on the method of production. For fundamental research, impulse voltages in the form of linearly rising ramp-shaped pulses are used until corona discharge or breakdown occurs. 'Double exponential impulse voltages' produced for experimental purposes have been standardized [14]. These voltages rise rapidly from zero to the Um peak value without significant oscillations and gradually return to zero. The waveforms used in impulse voltage experiments have defined shapes according to standards.

An impulse voltage is defined by four parameters: the waveform, the U_m peak value, the T_c front duration, the T_s tail half-value duration, and its polarity. Fig. 1 shows the time-dependent variation graph of an impulse voltage.

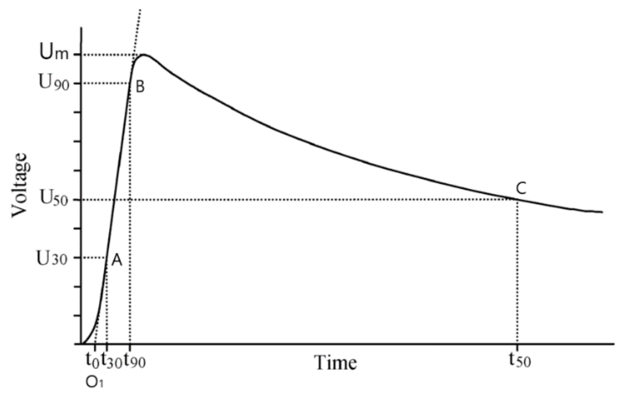

Fig. 1 Time-dependent variation of impulse voltage

In Fig. 1, the linear rise of the impulse voltage between the O_1 reference point and the U_m point, where the line connecting points A and B intersects the time axis, can be considered as the front of the impulse voltage. Therefore, the front duration (T_c) and the half-value width from the O_1 point to the U_{50} point (T_s) can be determined. The front duration (T_c) can be obtained by multiplying the time difference between the maximum value of the impulse voltage (U_m) and the point where it reaches 30% and 90% of its maximum value by a factor of 1.67 as seen in equation (1).

$$T_1 = 1{,}67 \,.\, T \qquad (1)$$

In addition to being defined as the time between O_1 and U_m, Ts is also the time between O_1 and the point where the voltage pulse reaches the U_{50} value. Double exponential impulse voltages consist of the difference between two decreasing exponential functions with time constants T_1 and T_2. Therefore, the front duration (T_c) and the half-value width (T_s)

can be obtained by multiplying T_1 and T_2 time constants by fixed coefficients (k_1=0.73, k_2=2.96). The relevant formulas are presented in equations (2) and (3).

$$T_c = k_2 . T_2 \quad (2)$$

$$T_s = k_1 . T_1 \quad (3)$$

The time constants T_1 and T_2 can also be calculated using the values of circuit elements. Different circuits of impulse voltage generators, namely type A and type B, are used for impulse voltage generation as seen in Fig. 2.

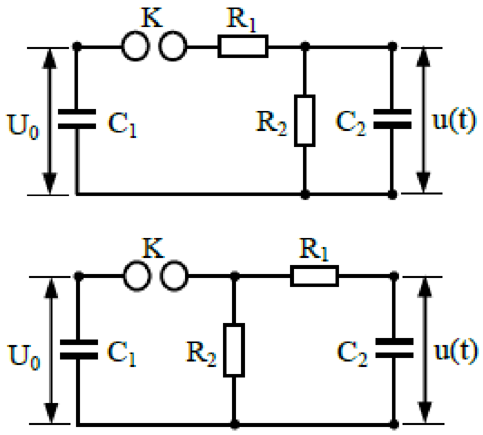

Fig. 2 Different circuits of impulse voltage generators

In these circuits, the impulse capacitor C_1 is charged to the voltage U_0 through a high-value load resistor, and it discharges through a spark gap between the K spherical electrodes. The desired u(t) impulse voltage occurs across the terminals of the C_2 capacitor. The impulse generator circuits are distinguished from each other by whether they are located behind or in front of the R_1 charging resistance, with respect to the R_2 discharge resistance. The values of circuit elements determine the shape of the impulse voltage with the help of equations (4) and (5).

$$T_1 = R_2(C_1 + C_2) \quad (4)$$

$$T_2 = R_1 . (\frac{C_1 . C_2}{C_1 + C_2}) \quad (5)$$

III. Assessment of Existing Impulse Generator

To generate the impulse voltage, an impulse voltage generator located in High Voltage Laboratory at Yildiz Technical University was used.

Fig. 3 Impulse voltage generator in laboratory

Fig. 3 shows a photograph of the impulse voltage generator and Fig. 4 shows the equivalent circuit diagram of the impulse voltage generator.

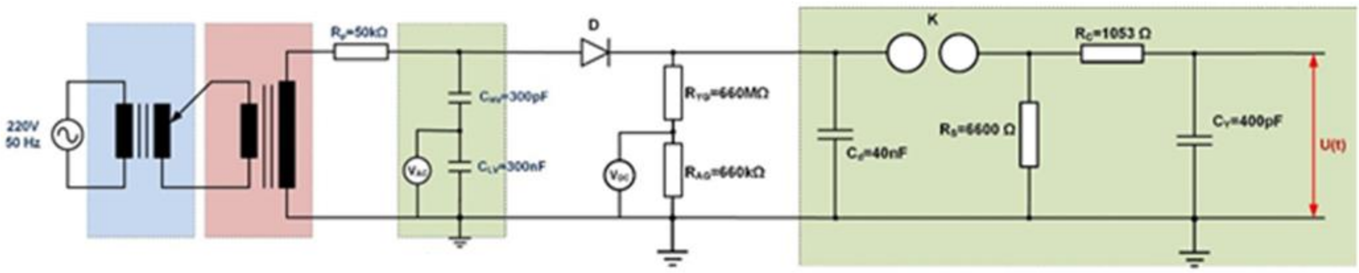

Fig.4 Equivalent circuit diagram of the impulse generator in high voltage laboratory

The impulse voltage generated in this circuit is the U(t) voltage at the output of the capacitive voltage divider, which is filled with a positive-polarity C_d impulse capacitor via the diode (D) at the output. Then, a breakdown occurs at the spherical electrodes (K), causing the C_d capacitor to discharge and generate the impulse voltage at the terminals of the C_y capacitor. In the high-voltage laboratory the impulse voltage generator circuit, the C_d impulse capacitor has a charging resistance of 1053 Ω and a discharging resistance of 6600 Ω.

The current impulse voltage generator circuit was tested without connecting any test samples to its terminals and with the system being shut down after the first breakdown. The resulting impulse voltage waveform is shown in Fig. 5 and Fig. 6.

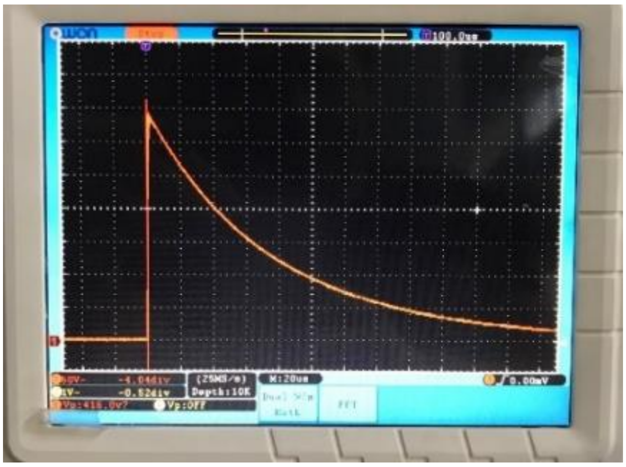

Fig. 5 An impulse voltage waveform

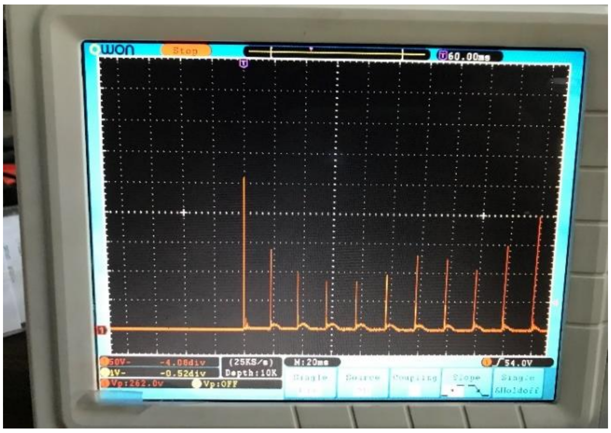

Fig. 6 Subsequential impulses waveform

As a result of the experiments, it was observed that the number of impulses was higher than the number of audible discharges and that the amplitudes of the impulses were variable. It was considered that this was due to the possibility of discharging through the resistive voltage divider at voltages lower than 100% of the C_d impulse capacitor's rated voltage. In this context, it was decided that a diode should be placed immediately before the C_d impulse capacitor to prevent unwanted incidents.

In order for the applied impulses to be counted and the capacitors not to be damaged by rapid charge-discharge and for the ionized particles to disperse in the air during jumping, a certain period of time must be observed between the successive voltage impulses. A resistance will be designed to control the time and this resistance will be used to charge the Cd impulse capacitor in 15 seconds. Thus, by providing one impulse in 15 seconds, 240 lightning impulse voltages per hour will be applied to the test samples.

Apart from this, a test sample was connected to the output of the lightning impulse voltage generator and the effect of the 900 pF capacitance value on the generator was checked. It has been noticed that the impulse voltage obtained with the inclusion of the test sample in the system, goes beyond the tolerances specified in the relevant standards and turns into an impulse voltage with a 4 µs front time and a 70 µs ridge half value time. As a result, it was decided that the filling and discharge resistance values in the impulse voltage generator circuit should be recalculated and tested with simulation.

IV. SIMULATION STUDY

A simulation study was carried out using MATLAB/Simulink software in order to design and control the specified development studies. The circuit diagram created in the MATLAB software is presented in Fig. 7.

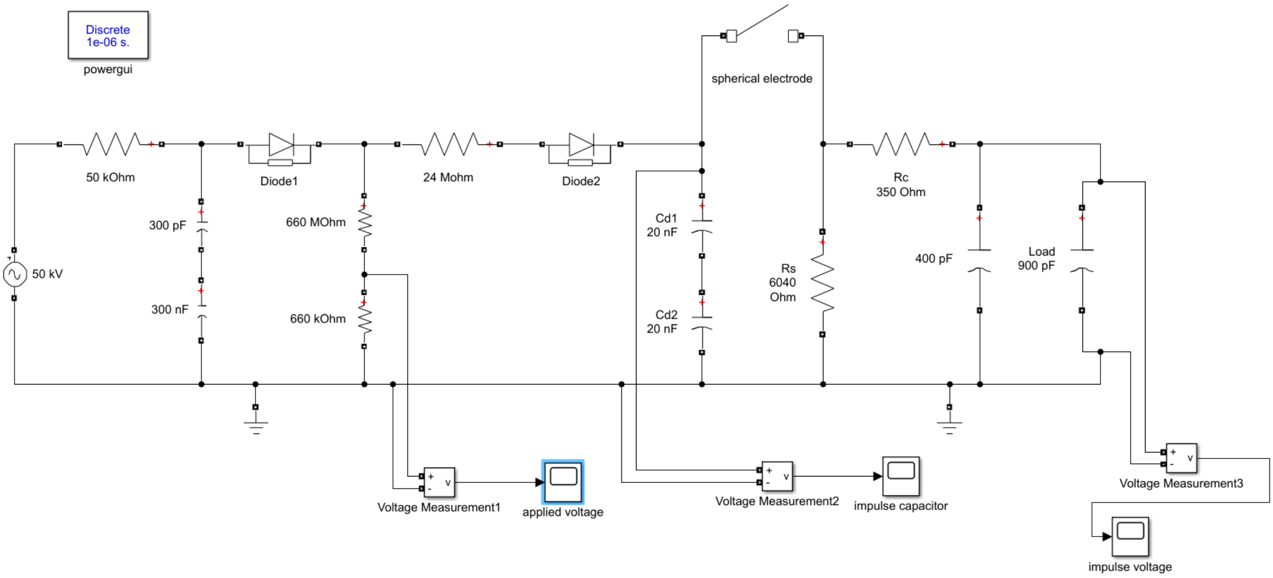

Fig.7 Circuit diagram of impulse generator in MATLAB

The simulation study was carried out separately for the loaded and unloaded cases by applying voltage at 50 kV amplitude and 50 Hz frequency. The spherical electrode arrangement is modeled using a normally open switch that is timed to turn off automatically.

With simulation study, a resistance value of 24 MΩ was obtained to set the time taken for two 20 nF impulse capacitors connected in series to fill at the voltage level we applied with the test transformer, to be 15 seconds. In addition, a diode is included in the impulse voltage generator circuit to prevent the impulse capacitor from being discharged through the ohmic voltage divider without jumping in the spherical electrodes, in order to avoid the problem experienced during operation under continuous voltage. This diode is shown in Fig. 7 as named diode2.

The voltage waveform formed at the ends of the impulse capacitor when 50 kV, 50 Hz voltage is applied with the test transformer is shown in Fig 8.

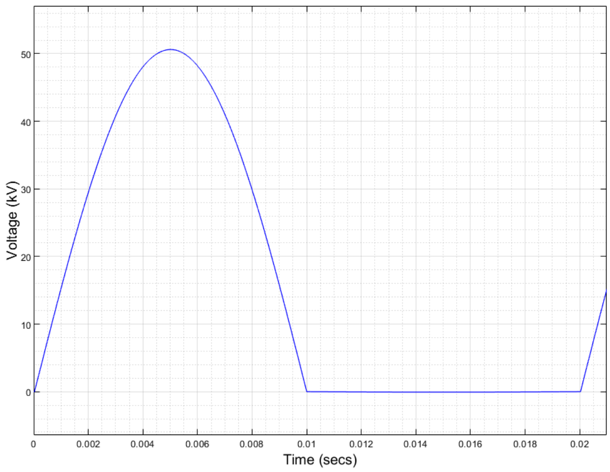

Fig. 8 The voltage waveform of the impulse capacitor

It is seen in detail in Fig. 9 that the voltage formed at the ends of the C_d impulse capacitor reaches 50 kV in 15 seconds with the addition of a 24 MΩ resistor to the circuit. In this context, when 50 kV and 50 Hz voltage is applied to the impulse capacitor, it is possible to generate impulse voltage periodically every 15 seconds.

In addition, the discharge of the pulse capacitor over the ohmic voltage divider is prevented by adding a diode to the pulse voltage generator circuit. Thus, the impulse voltages obtained during working under voltage will be directly transferred to the load and continuity will be ensured.

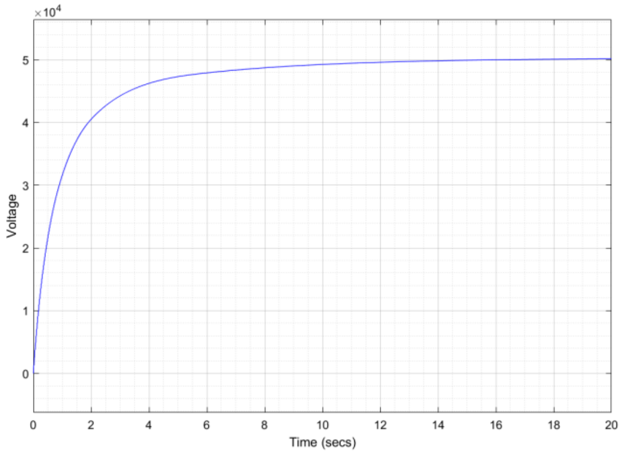

Fig. 9 Impulse capacitor reaches 50 kV in 15 seconds

Finally, the charging and discharging resistances located after the spherical electrodes need to be recalculated to correct the case that the impulse voltage graph changes to have durations of 4/70 µs due to the capacity of the test sample included in the circuit assembly. In addition, the theoretically calculated values will be examined with the simulation program and the results will be evaluated.

First, the time constants T_1 and T_2 were calculated with equations (2) and (3). The calculated T_1 and T_2 time constants were replaced in equations (4) and (5), and the charging and discharge resistance values were obtained again. In the light of the information obtained as a result of the calculation, the simulation study was repeated for the loaded state of the impulse generator.

The value of the circuit elements is C_1=10 nF and when the test sample (900 pF=0.9 nF) is connected in parallel to the 0.4 nF capacitor in the circuit assembly, the capacitor value obtained is C_2=1.3 nF.

When calculating the T_1 value,

$$50 \cdot 10^{-6} = 0.73 \cdot T_1 \tag{6}$$

$$T_1 = 68.32 \cdot 10^{-6}\ s \tag{7}$$

In order for the duration of T_s to be 50 µs, the time characteristic of the impulse voltage was calculated as T_1=68.32 µs, taking into account k_1=0.73.

When calculating the R_2 value,

$$68.32 \cdot 10^{-6} = R_2(10 \cdot 10^{-9} + 1.3 \cdot 10^{-9}) \tag{8}$$

$$R_2 = 6036\ \Omega \tag{9}$$

The value of R_2 discharge resistance calculated as 6036 Ω was used as 6040 Ω in the simulation study.

When calculating the T_2 value,

$$1.2 \cdot 10^{-6} = 2.96 \cdot T_2 \tag{10}$$

$$T_2 = 0.4 \cdot 10^{-6}\ s \tag{11}$$

In order for the duration of T_c to be 1.2 μs, the time characteristic of the impulse voltage was calculated as T_2=0.4 μs, taking into account k_2=2.96.

When calculating the R_1 value,

$$0.4 \cdot 10^{-6} = R_1 . \left(\frac{10 \cdot 10^{-9} \cdot 1.3 \cdot 10^{-9}}{10 \cdot 10^{-9} + 1.3 \cdot 10^{-9}}\right) \tag{12}$$

$$R_1 = 352\ \Omega \tag{13}$$

The value of R_1 discharge resistance calculated as 352 Ω was used as 350 Ω in the simulation study.

The lightning impulse voltage obtained as a result of the simulation studies has a peak value of 43 kV, front duration of 1.2 μs and a tail half-value duration of 50 μs. Impulse voltage waveform is shared in Fig.10.

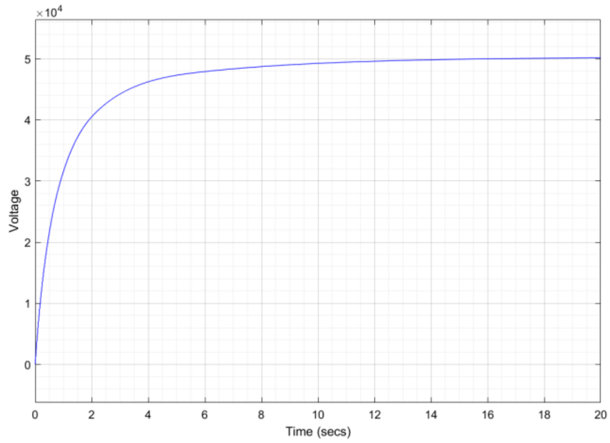

Fig. 10 Impulse voltage waveform in simulation study

In the waveform obtained as a result of the simulation study, the time difference (T) between 30% U_m (A point) value and 90% U_m (B point) value of the impulse voltage value was measured as 727.375 ns. When this value is substituted in equation (1), the front duration is calculated as 1.21 μs so that, the simulation value is verified.

V. Experimental Study

In this section, the relevant circuit elements have been created in the light of the information obtained as a result of the calculation and simulation studies, and information about the experimental lightning impulse generator installation has been shared. In Fig. 11, circuit elements consisting of resistors and diodes are seen.

Fig. 11 Creaiton of circuit elements of impulse voltage generator

The circuit elements necessary for the pulse generator to work properly under load are formed by using watt resistors on perforated pertinax. Resistors are connected to each other with hot solder. In addition, possible discharges are prevented by using insulation spray. The circuit elements formed are positioned in a plastic pipe with a diameter of 200 mm, thus air insulation is provided. A seamless contact surface has been obtained by forming the connectors from aluminum blocks.

Fig. 12 shows the impulse voltage generator installed in the high voltage laboratory.

Fig. 12 Impulse voltage generator installed in the high voltage laboratory

After the installation of the lightning impulse generator was completed in the laboratory, testing measurements were made on the different samples. The resulting impulse voltage waveform is shown in Fig. 13.

Fig. 13 An impulse voltage waveform after development

Upon examining the impulse voltage waveform, it can be said that it is suitable as it falls within the tolerances specified in IEC 60060-1 standard.

VI. Discussion

The development study carried out basically consists of three stages. The first is the evaluation part where the impulse voltage generator in the high voltage laboratory is evaluated and theoretical calculations are made. The second is the whole of the studies in which simulation studies are carried out and the calculated values are tested. The third and final stage consists of the experimental setup of the impulse voltage generator after the theoretical and simulation study evaluations.

Considering that similar studies in the literature include one or two of the three stages, it is clearly seen that the lightning impulse generator development study carried out for practice will benefit researchers in similar fields. In order for the development work to be considered successful, all stages must be feasible and test measurements must meet the constraints specified in the relevant standards. In this context, as a result of the test measurements, it has been determined that the impulse voltage generator in the high voltage laboratory of Yıldız Technical University can apply sequential impulse voltage in loaded and unloaded conditions and that various high voltage equipment can be used for tests. This confirms the success of the development work.

VII. Conclusion

This study aimed to develop a lightning impulse generator that is suitable for use in the High Voltage Laboratory of Yildiz Technical University. Changes were made to the structure of the impulse voltage generator to allow the application of lightning impulse voltage consecutively every 15 seconds. In this context, the results obtained from the study are presented below;

- The impulse voltage waveform produced by the impulse generator is highly dependent on the operating conditions.
- The circuit parameters of the impulse generator should be reviewed in order to obtain impulse voltages in accordance with the relevant standards in loaded conditions.
- Theoretical calculations should be done together with simulation studies.
- The numerical values of the circuit parameters obtained from the development studies should be experimentally applicable.
- Experimental validation must be performed following development studies.

As a result, the theoretical findings obtained through simulation were experimentally verified, and the development of lightning impulse generator was completed.

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