

# Novel 0.1 Hz Exponential Wave Generator Based on Semiconductor Switch

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**Abstract**—Very low frequency (VLF) high voltage technique has been used to some extent in the past for the field test of XLPE power cables. Equipment available has used 0.1 Hz voltage having a variety of waveforms such as square waves, triangular waves, etc. This paper describes a novel laboratory test system conducted with the objective to develop an exponential wave generator as the complement of existing VLF test waveforms. The generator consists of a high voltage (HV) 50 Hz AC source, a HV semiconductor switch unit based on the series-connected IGBTs, and shape-control resistors. The proposed HV switch can block 20 kV rated voltage and has the current capacity of 40A. Finally, the new designed approach permits the cable load of up to 1 $\mu$ F to be tested at a withstand voltage level of 20 kV. Preliminary experiments are performed in the laboratory using the proposed generator and the output waveforms are presented. The experiment results show that the exponential wave appears to be a satisfactory alternate to the waveforms used in the traditional VLF test and the generator is a utility installation for the diagnostic test of power cables.

**Keywords**—VLF; test systems

## I. INTRODUCTION

Recent publications in the technique community have shown that Very Low Frequency (VLF) test of XLPE power cables at 0.1 Hz has increasingly gained interests during the past 10 to 15 years [1]. The basic idea in using VLF test for the diagnostic test is to take advantage of the low charging current required to charge the specimen to a high voltage over a relatively long time interval [2]. Moreover, the dissipation factor ( $\tan \delta$ ), which is an important parameter for identifying the water tree content in a cable or the presence of other defects in the insulation or terminations, obtained during VLF test is much larger than at power frequency test, giving advantage of reducing the sensitivity requirement of the testing system.

The two most commonly used VLF technologies differ in the wave shapes of 0.1 Hz AC voltage. The sinusoidal waveform technology features a continuously sinusoidal waveform with a period time of 10 seconds, while the cosine-rectangular waveform technology generator a 0.1 Hz rectangular waveform with a cosine-shaped rising and falling edge which lasts 2 to 6 milliseconds. The topology of the former waveform generator is presented in [3], which uses a low-pass filter to convert the high frequency sinusoidal-wave-enveloped voltage waveform into 0.1 Hz waveform and has the voltage level of only 2.4 kVp-p. The latter waveform generator is described in [4],

which includes a complex software for controlling the digital signal processor (DSP).

This paper proposes a new approach to the VLF test. We developed a 20 kV rated 0.1 Hz exponential waveform generator, which has the advantage of lower cost, equipment size and simpler in structure over other technologies. Preliminary experiments on the capacitive specimen are performed using the generator in the laboratory, showing that the deliberate engineering development effort is applicable on the  $\tan \delta$  test.

## II. OPERATION PRINCIPLE OF PROPOSED EXPONENTIAL WAVE GENERATOR

A detailed design and diagram of the generator is described in this section.

### A. Circuit Description

Figure 1 shows the circuit diagram of the exponential wave generator. The input power is directly obtained from the normal 220V power frequency source. The output voltage amplitude is controlled by the variable transformer T1, as depicted in fig. 1. Controlled using optical fibres, P1, the polarity HV switch, consists of two major units, the forward conducting switch Q1 and the reverse conducting switch Q2. R1 is the current limiting resistor, preventing the step up transformer from transient over-current. C1 is the output voltage filter of P1, and R2 acts as the shape regulator of the output voltage on the capacitive specimen. S1 and S2 are AC switch pairs, turning on and off periodically to coordinate with P1 to protect the transformer core of T2 from saturation.

Operating principle of our schematic is depicted in Figure 2, where  $v_g$  is the gate control voltage of the gate-controlled equipment and high level of  $v_g$  means turning on the corresponding device. As can be seen, Q1 and Q2 perform alternately conducting process which lasts only half of the whole period of time ( $t_0 \sim t_4$ ). Turning on the forward switch Q1 charges the specimen to the preset positive voltage ( $t_0 \sim t_1$ ) through the shape-controlling resistor R2, then Q1 is turned off and Q2 is turned on, discharging the specimen ( $t_1 \sim t_2$ ) and recharging in a negative way ( $t_2 \sim t_3$ ). Finally, Q1 is turned on again and Q2 is turned off, and the generator operates in discharging process at the negative voltage ( $t_3 \sim t_4$ ). S1 is turning on during the charging process, whereas S2 is conducted during the discharging process to offer a reverse current path in case of the saturation of the core.

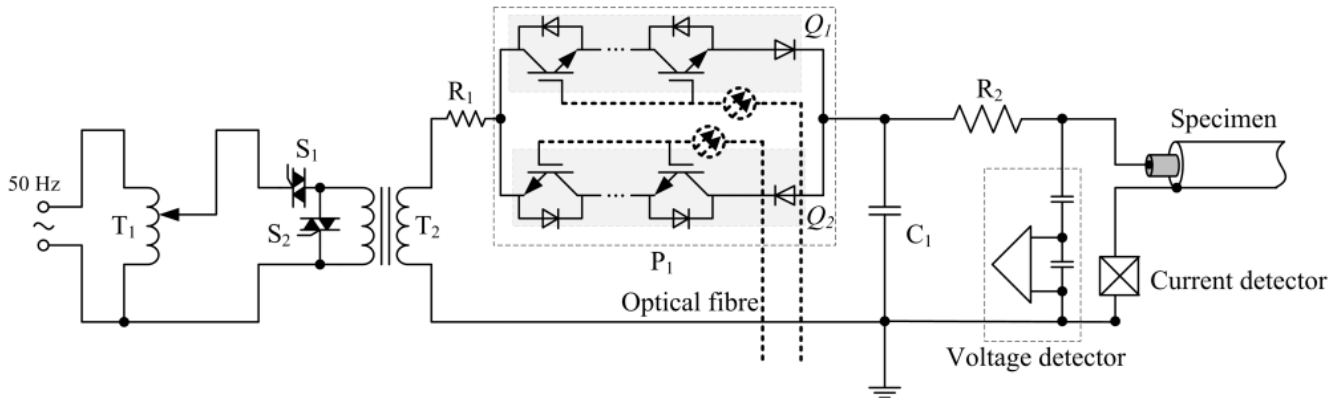


FIGURE I. THE STRUCTURE OF PROPOSED EXPONENTIAL WAVE GENERATOR.

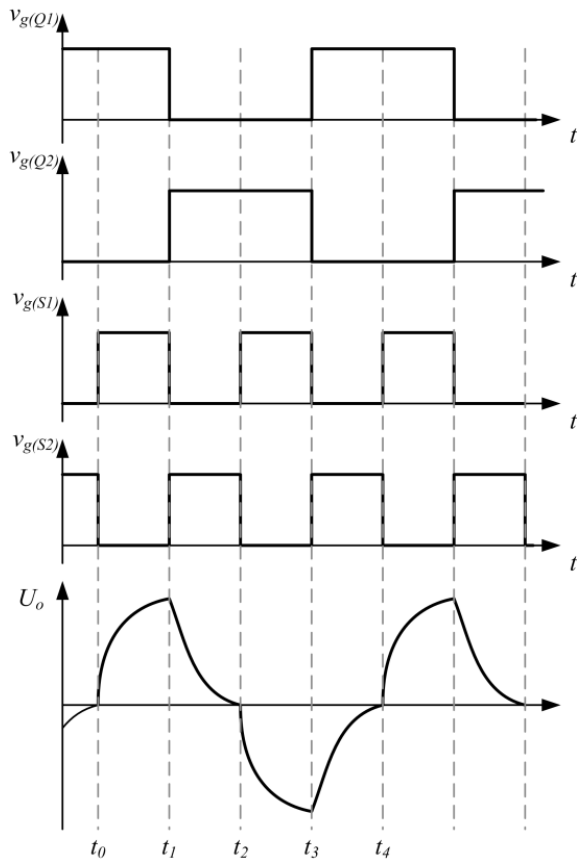
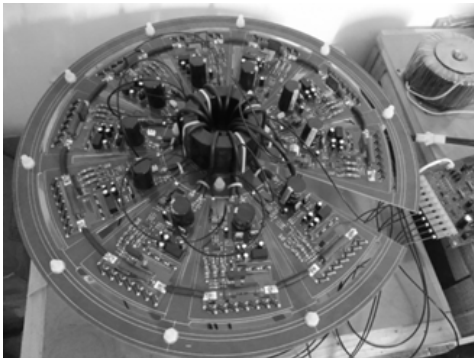
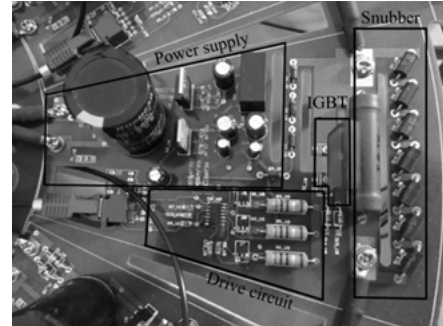


FIGURE II. TYPICAL WAVEFORMS OF THE PROPOSED GENERATOR.



(A)



(B)

FIGURE III. THE APPEARANCE OF PROPOSED HV SWITCH: (A) OVERALL DESIGN; (B) DETAILS.

### B. Design of the High Voltage Switch

The Structure of the proposed HV switch is shown in Figure 3. It consists of several main assemblies: a switch stack, a power supply system and the trigger unit. Each stack is made up of several series connected IGBT switch units (SUs), namely the IGBT chips, their accessory drive circuits, power-supply outputs and the snubbers. Thanks to the voltage balancing methods, which are paralleled statistic voltage sharing resistors and a series of dynamic voltage sharing transient voltage suppressors, each IGBT is rated only for an identical fraction of the full blocking voltage. To reach the blocking voltage requirement of 20 kV, nine IGBTs should be used as a basis if each of them carries the anticipate voltage of 2.5 kV, margin reserved for reliability operation. Considering the size and shape of the stack, redundancy concept is used. So the developed stack is configured as ten IGBT SUs connected in total, with each rated for 2 kV.

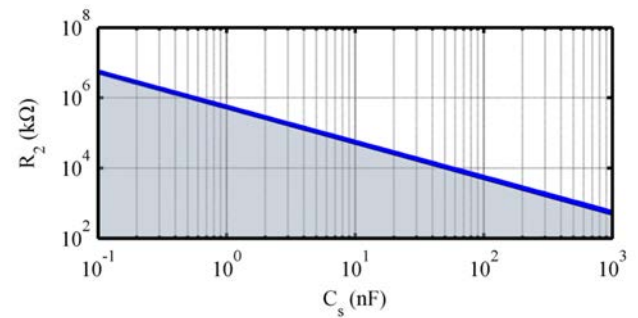
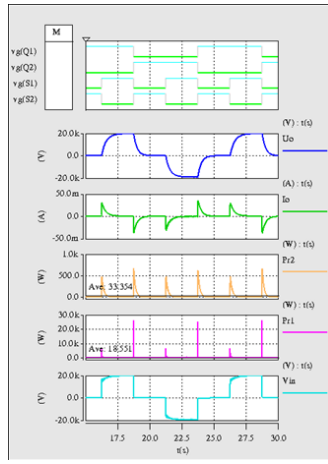
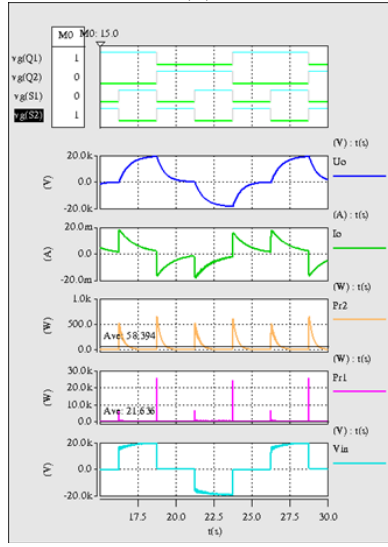


FIGURE IV. PERMISSIBLE REGION FOR R2 AS A FUNCTION OF CS



(A)



(B)

FIGURE 5. THE SIMULATION WAVEFORMS OF THE EXPONENTIAL WAVE GENERATOR AT (A)  $C_s = 500$  nF AND (B)  $C_s = 1$  μF.

GATE CONTROL VOLTAGE OF Q1,  $V_{G(Q1)}$ ; GATE CONTROL VOLTAGE OF Q2,  $V_{G(Q2)}$ ; GATE CONTROL VOLTAGE OF S1,  $V_{G(S1)}$ ; GATE CONTROL VOLTAGE OF S2,  $V_{G(S2)}$ ; OUTPUT VOLTAGE ON THE SPECIMEN,  $U_o$ ; CURRENT FLOWING THROUGH THE SPECIMEN,  $I_o$ ; POWER DISSIPATION ON R2, PR2; POWER DISSIPATION ON R1, PR1; VOLTAGE ON C1,  $V_{in}$ .

### C. Parameter Specification and Simulation Analysis

As can be seen from Figure 2, voltage on the specimen  $U_o$  in one period of time could be deduced as

$$U_o = \begin{cases} V_{in}(1 - e^{-\alpha(t-t_0)}), & t_0 \leq t \leq t_1; \\ V_{in}e^{-\alpha(t-t_1)}, & t_1 \leq t \leq t_2; \\ V_{in}(1 - e^{-\alpha(t-t_2)}), & t_2 \leq t \leq t_3; \\ V_{in}e^{-\alpha(t-t_3)}, & t_3 \leq t \leq t_4; \end{cases} \quad (1)$$

Where  $V_{in}$  is the voltage on C1, and  $\alpha$  is the parameter defined as

$$\alpha = \frac{R_2 + R_s}{R_2 C_s R_s} \quad (2)$$

where  $C_s$  and  $R_s$  respectively are the equivalent capacitive and resistive value of the specimen. In most cases, the value of  $R_s$  is very large (thousands of MΩ) and can be neglected.

It should be mentioned that the shape of the generator output voltage is varied with the capacitive value of the specimen, which is linearly related to the length of the cable to be tested. Assuming that the specimen is charged to the voltage level no less than  $kV_{in}$  as defined above during time interval of  $t_0 \sim t_1$ , we could get

$$V_{in}(1 - e^{-\frac{\alpha T}{4}}) \geq kV_{in}, \quad 0.9 \leq k < 1 \quad (3)$$

Where  $T$  is the period time of the exponential wave ( $T = 10$  s), derived from (3),

$$R_2 C_s \leq -\frac{T}{4 \ln(1 - k)}, \quad (4)$$

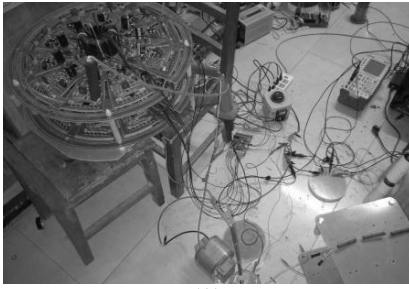
Figure 4 shows the operation range for selecting R2, where the parameter  $k$  is specified as 0.99. From Figure 3 we can see to guarantee that the circuit is properly operated under the maximum load condition of 1 μF as mentioned above, the minimum value of R2 is 540 kΩ. In the following paragraph we chose  $R_2 = 500$  kΩ to meet the worst-case requirement.

The performance of the generator designed was evaluated using SABER Sketch simulation package. A number of simulations were run for varying output voltage and load conditions. Various waveforms obtained demonstrated that the output of the generator is consistent with the theoretical waveforms. Some sample waveforms obtained with the variation of  $C_s$  are shown in Figure 5. We can see that because of the reduced value of load, the charge and discharge speed in Figure 5(a) is much faster than in Figure 5(b), results in the variation of the wave shape.

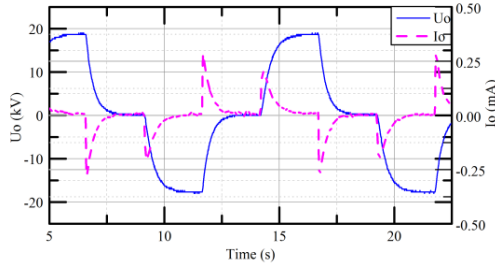
### III. EXPERIMENTAL RESULTS AND APPLICATION

To verify the aforementioned analysis, a laboratory exponential wave generating system is built. To refine the voltage shape under the specified load condition, the specifications of the system are as follows:  $R_1 = 15$  kΩ,  $R_2 = 6$  MΩ,  $C_1 = 200$  nF. T1: 220V input, 500W varitrans; T2: 220V to 20kV, 500W step up transformer; S1, S2: 1 kV, 50A AC switch; Q1, Q2: proposed HV switch series connected with 40kV, 1A silicon stack.

The experimental setup is depicted in Figure 6(a) and the results are given in Figure 6(b) the specimen parameters are  $C_s = 50$  nF and  $R_s = 1660$  MΩ. In Figure 6(a) we can see the amplitude of output voltage is 20 kV, and the wave shape is similar with the simulating results, which is the proposed exponential wave.



(A)



(B)

FIGURE VI. (A) EXPERIMENT SETUP AND (B) OUTPUT WAVEFORM.

#### IV. CONCLUSION

On the basis of the development of a 20 kV double module switch built up with commercially available IGBTs, a novel 0.1 Hz exponential wave generator is designed and tested in the laboratory. Simulating results are proposed, showing that the system could generate expected waveform under various load condition. To refine the wave shape under the worst case, system parameters are calculated and specified. We setup a prototype and the feasibility of this scheme is proved by the produced exponential wave of anticipated rate of 20 kV. It should be mentioned that the further application of the generator is to calculate the dissipation factor ( $\tan \delta$ ) and dielectric spectrum by using the excitation voltage  $U_o$  and the response current  $I_o$ . Compared with traditional sinusoidal 0.1 Hz VLF generator, the exponential wave generating system allows analyses of harmonics as well as the fundamental frequency. Further research on this kind of application will be proposed later.

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