A Single-Phase Voltage Sag Generator for Testing Electrical Equipments

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***Abstract*— This paper describes a transformer-based voltage sag generator (VSG) suitable to evaluate the susceptibility of electrical equipment to voltage sag. The built VSG utilized one auto-transformer and two solid state relays (SSRs) to provide nominal voltage and sag voltage to the load. The switch statuses of two SSRs are controlled by nominal voltage and sag voltage duration signal produced by electronic circuits. The VSG operating result shows that it enables effective control of sag magnitude, duration, beginning and ending points on output voltage wave. If needed, it can work as a voltage swell generator and a voltage interruption generator. By supplying high voltage (HV) transformer from the primary side, the VSG also can provide HV sag, swell, and interruption.**

The presented VSG is easier to set up in the lab, and the construction cost is much lower than buying VSG products at the current market.

***Index Terms*—Equipment susceptibility, voltage interruption, voltage sag, voltage sag generator, voltage swell.**

I. INTRODUCTION

Modern power systems are becoming more and more sensitive to the quality of supplied power. The reason is that not only does modern equipment include a vast variety of electronic components which can be very vulnerable to power disturbance, but also the customers become more susceptible to the losses produced by equipment malfunction. As one of the most common power disturbances, voltage sag typically happens randomly and usually lasts only a few cycles. However, sensitive equipment often trips or shuts down for those sags, even if nominal voltage returns in just a few cycles. Thus, voltage sag brings the greatest financial loss compared with most other kinds of power disturbances [1], [2].

There are some devices installed in power systems to mitigate voltage disturbance, such as uninterruptible power supply, voltage regulator, and dynamic sag restorers. These devices are effective but expensive. It makes more economic sense to improve the sustainability of electrical equipment so they can tolerate common power disturbances without additional support [3]. The VSG is a kind of device which can supply reliable and repeatable voltage sags to measure equipment susceptibility to the voltage sags. With the help of the VSG, engineers can have improved knowledge about the equipment susceptibility to voltage disturbance, and further adjust the design of the equipment [4], [5]. Moreover, some standard methodologies have proposed recommended performance limits for equipment response to voltage sag with specific voltage sag magnitudes and durations. To fulfill these recommendations, engineers need the help of the device like the VSG [1], [6], [7].

Depending on different realization methods, there are four types of VSGs, which are amplifier-based, transformer-based, switching-impedance-based, and generator-based. Amplified-based VSG generates output voltages and currents with desirable characteristics by using a waveform generator and power amplifier. It can provide voltage sags with varying magnitude, duration, frequency and harmonics. Normally amplified-based VSG is more complicated and expensive than transformer-based VSG [8]. Transformer-based VSG is usually realized as a combination of transformers and appropriate switching devices. It can not provide changeable frequency and harmonic distortion. However it is low cost, and it is easily constructed in the lab [9]. Switching-impedance-based VSG creates voltage sags by switching impedance into a power system by using the thyristor controlled reactor (TCR). It can provide harmonics by controlling firing angles of the TCR. Switching-impedance-based VSG is good at testing equipment in HV power circuits [10]. Generator-based VSG provides voltage sag by changing the exciting current of the generator. The weight and scale of the generator are the challenges [2]. Since transformer-based VSG is capable of generating the sag defined in reference [1] - a decrease in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min, it has more economic and reliability advantages than the other three types of the VSG.

Some VSG products are already selling in the current market, such as Industry Power Corruptor by Power Standard Lab, and Porto-Sag by EPRI PEAC Corporation. They work well, however they are very expensive. In this paper, we propose a transformer-base VSG, which is very easy to construct in the lab, and has low cost - less than $300.

This work was supported by Power Systems Engineering Research Center (PSERC).

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II. Structure of the VSG

The structure of the VSG is demonstrated in Fig. 1. Four parts are needed for the realization of the transformer-based VSG:

1) Duration control circuit, which regulates the duration of nominal voltage and voltage sag.
2) Signal shifting circuit, used to adjust sag beginning and ending points on voltage wave.
3) Drive circuit, providing nominal voltage or voltage sag based on the control signal generated by the signal shifting circuit.
4) Single-phase auto-transformer, for generating two voltage levels: nominal voltage and voltage sag.

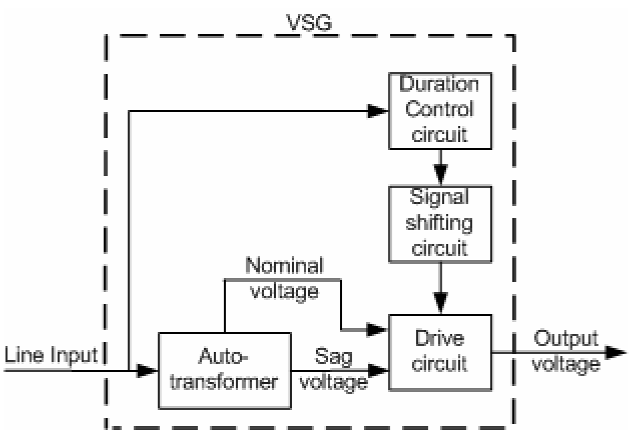


Fig. 1. The structure of the built transformer-based VSG

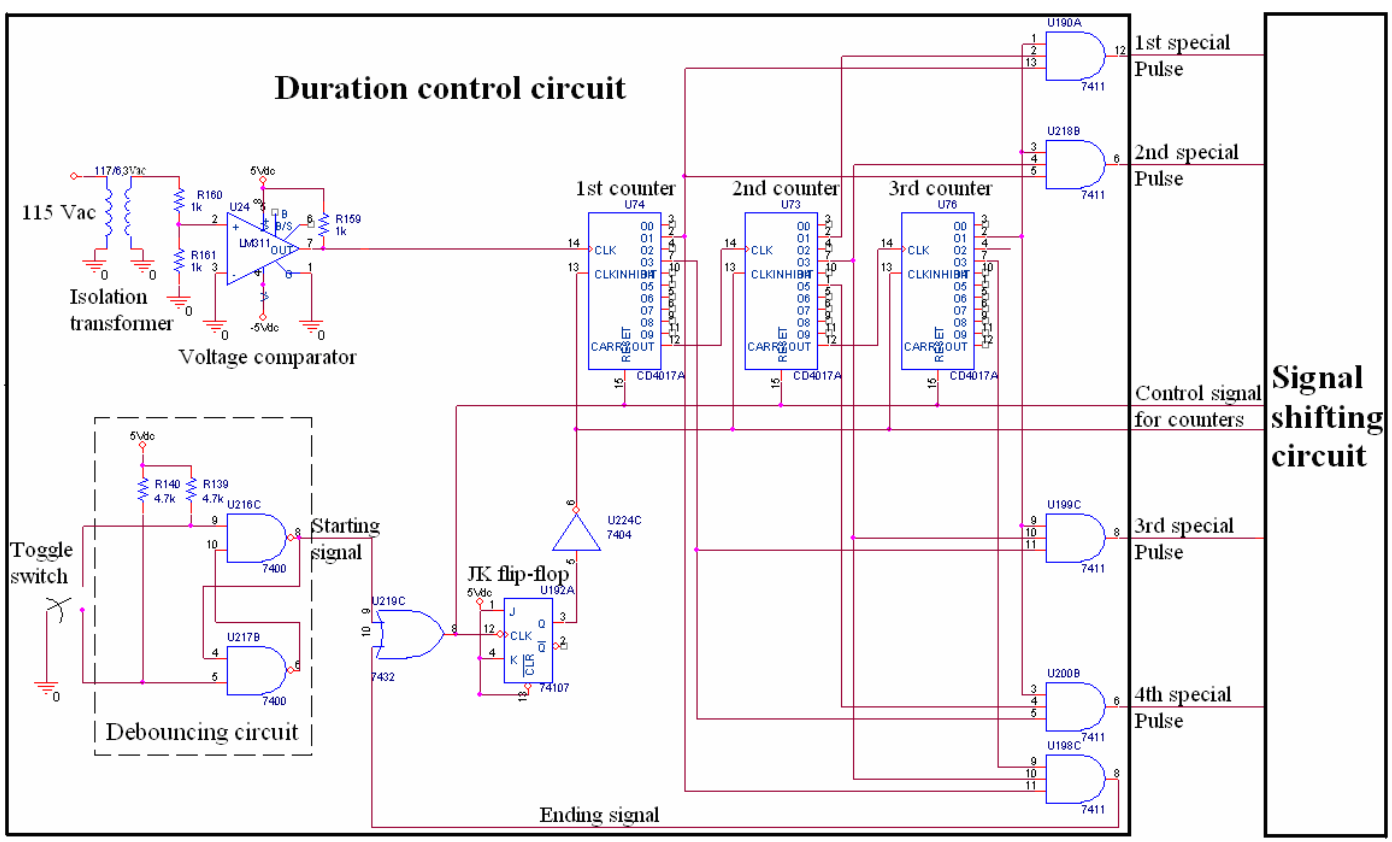
The functions of the duration control circuit, signal shifting circuit, drive circuit, and autotransformer are described below.

A. Duration control circuit

The duration control circuit was built and Fig. 2 shows its detailed hardware diagram for 20 cycles pre-sag nominal voltage, 2 cycles voltage sag, and 20 cycles post-sag nominal voltage. The circuit is composed of one voltage comparator (LM311), one JK flip-flop, three 10 decoded counters (CD4017), some 3-input AND gates (7411), etc.

The VSG was designed to operate after receiving a starting signal generated by an on-off-(on) toggle switch, and stop after getting an ending signal automatically produced by the duration control circuit. The debouncing circuit is used to mitigate the effects of mechanical toggle switch bounce, and provide smooth, reliable single pulse acting as a starting signal. The ending signal can be different according to the various voltage sag durations. In current design, the 115th pulse was selected to be the ending signal. The starting signal and ending signal are combined together by one OR gate. The combined signal is provided to the counters as reset signal and the JK flip-flop as its input. Since the JK flip-flop is falling edge-triggered, the output of the JK flip-flop will be low during the time after the falling edge of starting signal and before the falling edge of ending signal, which enable the counters begin to work. As a result the working time of the counters is controlled based on starting signal and ending signal and further VSG operation time is controlled.

The AC line voltage (115Vac) is supplied to voltage comparator through an isolation transformer (117/6.3Vac). The voltage comparator compares 3Vac with the ground, then output a synchronous voltage square waveform, which has the same frequency with the input AC source and 0.5 duty ratio. The synchronous voltage square waveform is supplied to the first counter as its clock signal. The carryout output (10 cycles duration and 0.5 duty ratio) of the first counter acts as the



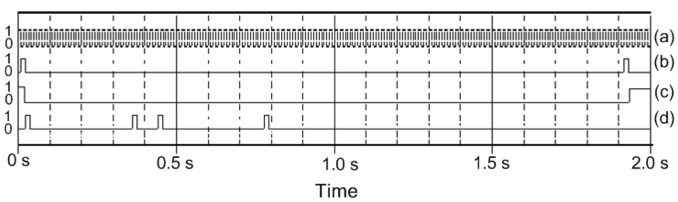
clock signal for the second counter. The carryout output of the second counter (100 cycles duration and 0.5 duty ratio) acts as the clock signal for the third counter.

By using three counters, any cycle after VSG initiation and before 1000th cycle can be captured individually. For example, if we want to get 123rd cycle, we just need to use 3-input AND gates to combine 1st pulse output of the 3rd counter, 2nd pulse output of the 2nd counter, and 3rd pulse output of the 1st counter, and then the output of 3-input AND gates will be the 123rd cycle.

Four special pulses/cycles are generated by the duration control circuit for regulating the duration of nominal voltage and sag voltage. The functions of these four specific pulses are as follows:

- 1st special pulse: Beginning pre-sag nominal voltage.
- 2nd special pulse: Ending pre-sag nominal voltage and beginning voltage sag.
- 3rd special pulse: Ending voltage sag and beginning post-sag nominal voltage.
- 4th special pulse: Finishing post-sag nominal voltage.

A PSpice simulation diagram was drawn to verify the design of the duration control circuit. Fig. 3 displays the simulation result of the duration control circuit, which includes the synchronous voltage square waveform generated by voltage comparator, starting signal, ending signal, enable signal for the counters, and the combination of four special pulses (1st, 21st, 26th, and 46th cycles) for 20 cycles pre-sag nominal voltage, 5 cycles voltage sag, and 20 cycles post-sag nominal voltage.



(a) Synchronous voltage square wave generated by voltage comparator
(b) Starting signal (left pulse) and ending signal (right pulse)
(c) Enable signal for the counters (VSG operation duration)
(d) The combination of four special pulses for 5 cycles sag, 20 cycles pre-sag nominal voltage, and 20 cycles post-sag nominal voltage

Fig. 3. The simulation result of the duration control circuit

Based on the different duration requirements for nominal voltage and sag voltage, the different four special pulses are generated, combined, and supplied to the signal shifting circuit.

B. Signal shifting circuit

Since voltage sag may begin and finish at any point of the voltage wave, a signal shifting circuit is built to shift the 2nd and 3rd special pulses which determine the beginning and ending of the sag. Fig. 4 shows the detailed hardware diagram of the signal shifting circuit. With the current VSG design, the pulse shifting circuits for the 2nd and 3rd specific pulse are the same, and the 2nd and 3rd specific pulse can be shifted up to 1 cycle afterward.

Fig. 5 shows the simulation result of the pulse shifting circuits simulated with the PSpice. The pulse is shifted by the following steps:

- The pulse (Fig. 5 (a)) with 1 cycle duration is inverted by one inverter (7404) and the inverted pulse is provided to one 555 timer. The inverter is used here for the 555 timer is falling edge-triggered. The output of the 555 timer is a prolonged pulse (Fig. 5 (b)) with 2 cycles duration.
- The pulse with 2 cycles duration passes the RC circuit composed of one 10 kΩ resister and one 1uF capacitor (as shown in Fig. 4), and becomes an exponential signal (Fig. 5 (c)).
- By using one voltage comparator (LM311), the exponential signal is compared with one adjustable voltage (Fig. 5 (c)) to get a delayed pulse (Fig. 5 (d)) compared to the original pulse. The delay time is determined by the high level duration of the prolonged pulse generated by the 555 timer and compared adjustable voltage of the voltage comparator.

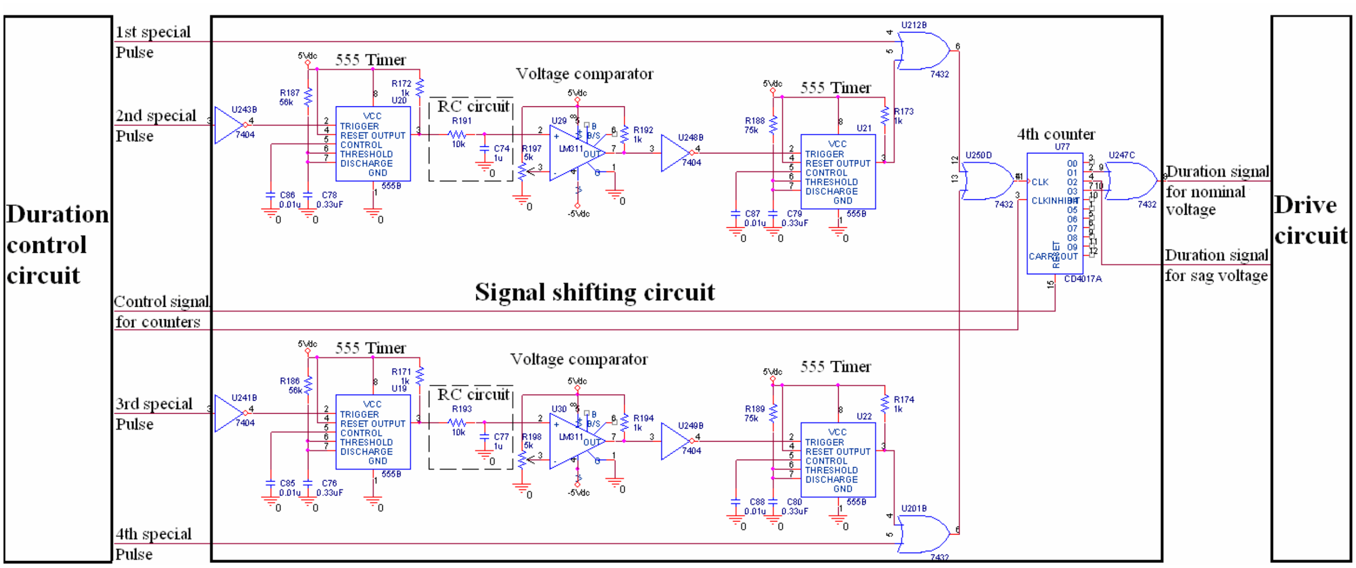


Fig. 4. The simulation diagram of VSG signal shifting circuit with 2 cycles sag duration

- One inverter and one 555 timer are used to stabilize the output signal of the voltage comparator.

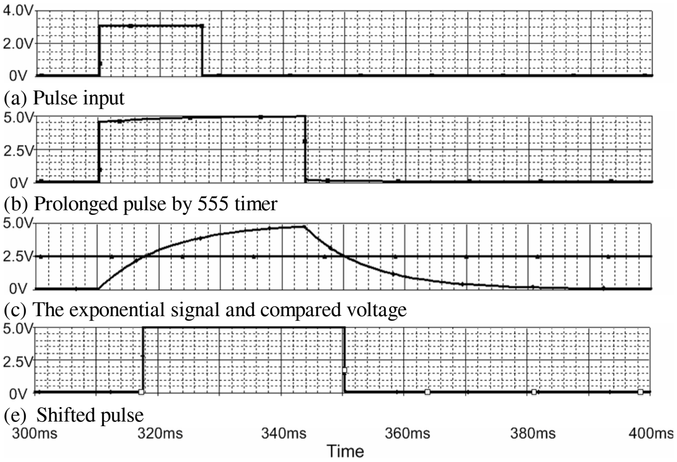
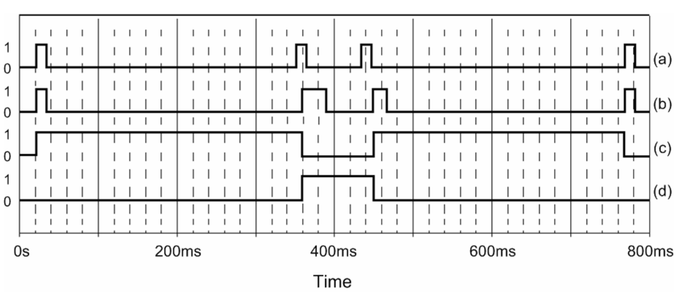


Fig. 5 Pulse shifting

The shifted 2nd and 3rd special pulses and un-shifted 1st and 4th special pulse are combined together and supplied to 4th counter. The 4th counter has the same reset signal and enable signal as the 1st, 2nd, 3rd counters. The 1st and 3rd output signals of the 4th counter are combined by an OR gate, and the combined signal is the final duration signal for nominal voltage. The 2nd output signal of the 4th counter is the final duration signal for sag voltage. The final duration signals for nominal voltage and sag voltage will be provided to the drive circuit.

Fig. 6 shows simulation result for the input and output signals of the signal shifting circuit. The 2nd pulse is shifted half cycle, the 3rd pulse is shifted one cycle, and the duration of sag voltage is actually 5.5 cycles.



(a) Four special pulses provided to the signal shifting circuit from the duration control circuit
(b) The 2nd and 3rd pulse are shifted afterward in the signal shifting circuit
(c) The combination of the 1st and 3rd output signals of 4th counter, which is control signal for nominal voltage
(d) The 2nd output signal of the 4th counter, which is control signal for sag voltage

Fig. 6 The input and output signals of the signal shifting circuit

C. *Drive circuit*

Fig. 7 shows the internal construction of the drive circuit and its connection with auto-transformer, signal shifting circuit and the load. The output voltage waveform of the drive circuit can be provided to a HV transformer to generate HV voltage sag for testing HV equipments.

Two non-zero crossing SSRs (S216SE1) – SSR1 and SSR2 were selected as the switches to provide output voltage with nominal voltage and voltage sag. The SSR1 is closed for nominal voltage, and the SSR2 is closed for sag voltage.

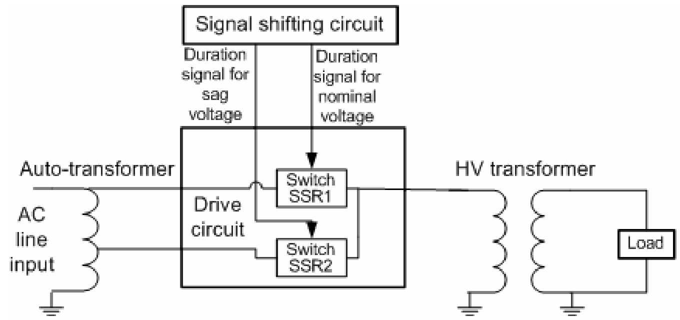


Fig. 7 The construction of the drive circuit

The switch statuses of the SSR1 and SSR2 are controlled by the duration signals generated by the signal shifting circuit. As a characteristic of the SSR, it switches on when there is a gate voltage applied to it, and switches off automatically when the gate signal disappears and the current passing it is zero. Accordingly when the drive circuit receives the duration signal for sag voltage, SSR2 is closed, while SSR1 will not be open until the current crossing it becomes zero. Similarly when the drive circuit receives the duration signal for post-sag nominal voltage, SSR1 is closed and SSR2 will stay close before the coming first current zero crossing. In some sense, the beginning and ending points of sag voltage on output voltage waveform are dependent on both the duration signal for sag voltage and the load.

The maximum output power of the VSG is determined by the characteristics of the SSRs, such as maximum load voltage and maximum load current. In the built VSG, the SSRs are changeable so the SSRs can be selected based on different requirements.

D. *Single-phase auto-transformer*

The purpose of including single-phase auto-transformer in the VSG is to provide two voltage sources (nominal voltage and sag voltage) to the drive circuits. In exchanging the nominal voltage source with the sag voltage source, the VSG will act as a voltage swell generator. In reducing sag voltage to less than 10% nominal voltage or un-connecting the sag voltage source with the drive circuit, the VSG can be used as a voltage interruption generator. The auto-transformer also can be replaced by two single-phase transformers to obtain the special magnitudes of nominal voltage and sag voltage.

III. VSG OPERATION

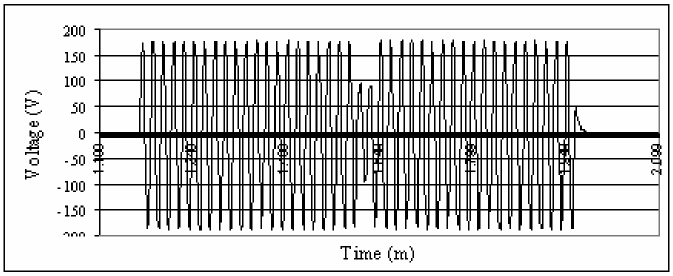
Table I shows the specifications of the built VSG.

TABLE I
SPECIFICATIONS OF THE VSG

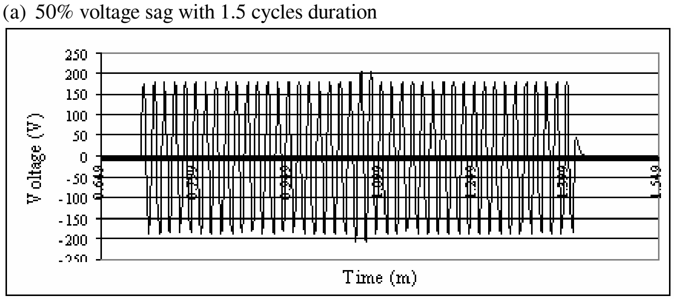
Control voltage	75 to 185 Vac
Operating frequency	45 to 65 Hz
Maximum load voltage	260Vac
Maximum load current	16Arms
Peak one cycle surge current	160A

Sag magnitude	0% to 100%
Swell magnitude	100% to 345%
Sag duration	0 to 16 second
Sag beginning and ending points on voltage wave	0 to 360°

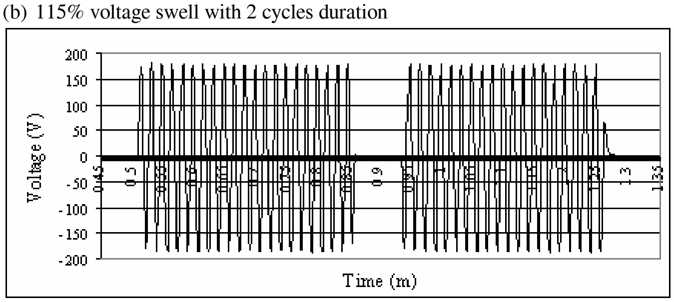
Fig. 8 shows three kinds of VSG operating results (voltage sag, voltage swell, and voltage interruption) captured by digital scope.



(a) 50% voltage sag with 1.5 cycles duration



(b) 115% voltage swell with 2 cycles duration



(c) Voltage interruption with 4.5 cycles duration

Fig.8. VSG operation results captured by digital scope

IV. Conclusion

As one of the concerns in power quality, voltage sag brings lots of troubles to the performance of electrical equipment. The VSG is widely used to evaluate equipment susceptibility to voltage sag. In the current market, there are some VSG products which are successful but are very expensive. A transformer-based VSG is presented in this paper, and it is easy to build in the lab with a comparable low cost. The operation result showed that the designed VSG is capable of controlling effectively the magnitude and duration of nominal voltage and sag voltage, and the starting point and ending point of the sag voltage.

With appropriate connection, the VSG also can work as voltage swell generator and voltage interruption generator. If needed, the VSG can provide HV sag, swell, and interruption by connecting with the primary side of the HV transformer.

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VI. Biographies

Yan Ma was born in Hegang, China. She received her B. S. degree and M. S. degree in Electrical Engineering from North China Electric Power University, Beijing, China. She is currently pursuing the Ph. D. degree at Arizona State University.

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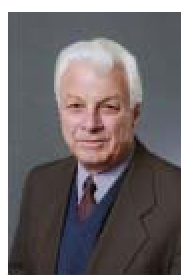

George Karady received his BSEE and Doctor of Engineering degrees in electrical engineering from the Technical University of Budapest.

Dr. Karady was appointed to Salt River Chair Professor at Arizona State University in 1986. Previously, he was with EBASCO Services where he served as Chief Consulting Electrical Engineer, Manager of Electrical Systems, and Chief Engineer of Computer Technology. He was Electrical Task Supervisor for the Tokomak Fusion Test reactor project in Princeton. Dr. Karady is a registered Professional Engineer in New York, New Jersey, and Quebec. He is the author of more than 100 technical papers.