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THREE PHASE CONTROL FOR PWM-SWITCHED AUTOTRANSFORMER VOLTAGE-SAG COMPENSATOR BASED ON PHASE ANGLE ANALYSIS

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ABSTRACT

Enhancing compensating capability is essential in a voltage-sag compensator. It involves two main aspects, first, sag detection technique and second, voltage sag compensator. Many detection techniques have been introduced to measure and to detect voltage sag, such as RMS-Value Evaluation and Peak-Value Evaluation. Unfortunately, most of the techniques require a delay for sag to be detected then compensated, whereas immediate sag detection is vital to improvement of transient performance. Presented is a three-phase PWM-switched autotransformer voltage-sag compensator that is based on AC-AC converter and that uses the proposed three phase controller based on Phase Angle Analysis as the detection technique. The significant advantage of this detection technique is the detection time. It is capable of detecting and compensating voltage sag the moment sag occurs without delay. Its effectiveness and capability were verified via MATLAB/Simulink simulation.

Keywords: *Voltage Sag, Voltage Sag Detection, Voltage Sag Compensator, RMS Detection, Peak Detection.*

1. INTRODUCTION

Sag detection is important as it determines the dynamic performance of a voltage-sag compensator. Research on voltage sag detection has also grown up and it is an essential part of the voltage sag compensator. It is the phenomenon of RMS voltage rapidly declining from 90% to 10% rated voltage, typically for 0.5 to 30 cycles [1]. Voltage sags commonly are caused by lightning, accidental short circuits, loose connections, the starting of large motors (or air-conditioners), or abnormal use of AC mains [2]. Short periods of voltage sag may cause irreversible damage to sensitive equipment and cause significant economic losses, owing to interrupted industrial production [3].

Disturbances caused by voltage sags cause losses to not only production but also utility [4-5], increasing demand for clean power as use of microelectronic processors increases in various types of equipment such as computer terminals, programmable logic controllers, and diagnostic systems. These are susceptible to disturbances in their supply voltage, and the widespread application of nonlinear electronic devices in power apparatuses and systems makes waveform distortion more significant.

One of the most popular topologies for voltage-sag compensators is the dynamic voltage restorer (DVR), which requires a voltage-source inverter (VSI) for line-injection of series voltage, an injection transformer, and a dc link. Its obvious disadvantage, however, is that is incapable of compensating deep and long-duration voltage sag. Increasing its capability requires more energy storage devices, increasing cost. Another consideration is environmental, as battery is the energy storage device. Also, voltage regulation of the dc link demands use of a separate ac-dc converter, which requires one more stage of power conversion, increasing size, cost, control complexity, and power losses [6].

Energy storage is unnecessary in AC-AC sag compensator, though an AC-AC converter is needed to convert dropped ac voltage to regulated ac voltage. The three-phase PWM-switched autotransformer voltage-sag compensator presented here uses an AC-AC converter and three-phase controller based on Phase Angle Analysis as the detection technique. The proposed detection technique is able to detect and compensate voltage sag the moment sag occurs with non disturbance to the output voltage signal.

2. VOLTAGE SAG DETECTION TECHNIQUES

Precise and fast voltage detection is essential to voltage sag compensation in determining the start and the end of a voltage sag occurrence as well as the severity of the sag. Methods of sag detection that have been introduced include RMS-Value Evaluation and Peak-Value Evaluation.

2.1 RMS-Value Evaluation Technique [2,3,8]

When determining the amount of power available to equipment, AC voltage and current measurements are made, thus sag voltages are usually expressed in RMS terms. With an RMS computation, though, information on phase and polarity is lost because RMS uses only the absolute magnitude of a signal. In other words, an RMS value is based on the averaging of a previous cycle's sampled data, therefore representing one cycle of historical average value, not a momentary, or an instantaneous, reading.

RMS values, continuously calculated for a moving window of input voltage samples, provide a convenient measure of magnitude evolution because they express a signal's energy content, assuming the window contains N samples per cycle (or half cycle). The widely-used moving-window RMS value is calculated for digitally recorded data as follows. Each sampled component of one cycle of the waveform is squared, then the squares summed. The square root of this sum is then calculated, the single value plotted.

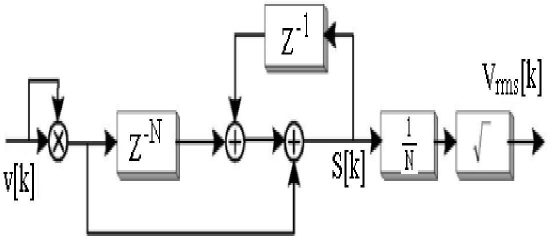
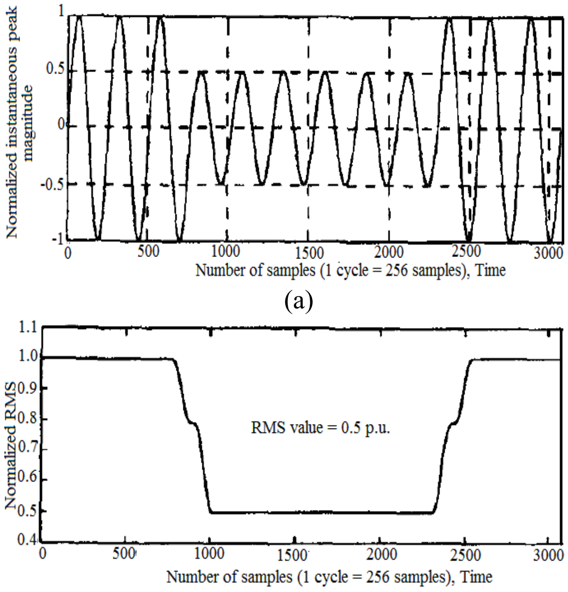


Fig. 1: RMS magnitude evaluation by using a moving window

The basic idea is to follow the voltage magnitude changes as close as possible during the disturbing event. Figure 1 represents the RMS magnitude evaluation process through a moving window. The more RMS values are calculated, the closer the disturbing event is represented, especially the non-rectangular variations.



(a)

(b)

Fig. 2: (a) Ideal voltage-sag waveform (b) RMS of the sag waveform

Figure 2(a) shows ideal voltage-sag, i.e., the transition occurring at zero-crossing and there is no distortion during the sag. The sag has a 50% depth and occurs for about 6-cycle steady-state duration. Figure 2(b) shows the RMS plot through the moving-window RMS computational technique based on Figure 2(a). The plot shows a one-cycle transition occurring before the 0.5 p.u. value is reached, and a one-cycle rise to recovery. The slow transition is due to the moving window retaining almost one cycle of historical information in the calculation.

2.2. Peak-Value Evaluation Technique [7,8,9]

Figure 3 shows the block diagram of voltage measurement that uses peak detection. $V_{measure}$, as Figure 3 shows, represents the single-phase line-to-neutral voltage. The voltage is shifted 90º by using a 90º shifter to obtain a cosine value. Assuming the line frequency is 50Hz, the 90º shifted value can be obtained by either an analog circuit or by digital signal processing. Both voltage components are squared and summed to yield V_p^2. Peak value is then obtained by squaring the root of V_p^2. The significant advantage of peak-value evaluation over other methods is that it needs only single-phase values.

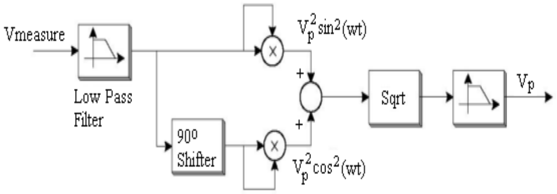


Fig. 3: Block diagram of the Peak detection technique

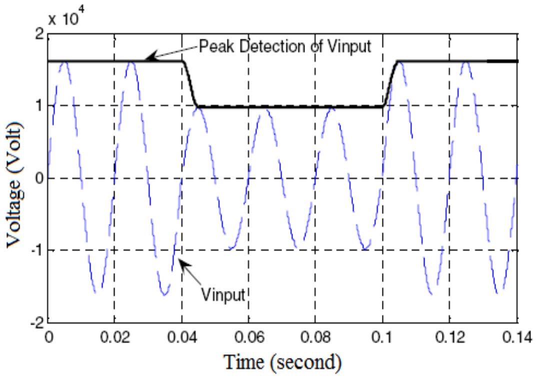


Fig. 4: Peak detection signal and Vinput versus time.

Figure 4 shows the output value of the peak-detection block compared with the input voltage. The comparison verifies the method's ability in detecting the input signal's peak value in the least possible time. The detection took at least a quarter of a cycle.

3. PHASE-ANGLE ANALYSIS FOR VOLTAGE SAG DETECTION

RMS-value evaluation and peak-value evaluation take one cycle and at least a quarter of a cycle, respectively, to detect, and compensate voltage sag. The reason is; the voltage controller used in the detection needs the voltage-sag information for at least a quarter of a cycle.

The author finds that there is no necessity in retaining for some time, the voltage-sag information, as the following proves: Figure 5 represents the half cycle of a sinusoidal at normal voltage with peak value of 100V, and 90% 80%, 70%, 60%, and 50% voltage sags. L6 is a vertical line intersecting at 90° all the sinusoidal waveforms. The differences in voltage amplitudes among various voltage sags are clearly shown. L5, L4, L3, and L2 are vertical lines intersecting the sinusoidal waveform, at phase angles 72°, 54°, 36°, and 18°, respectively. From L5 to L2, the differences in voltage amplitudes for various voltage sags are also significant. Detection of voltage sag is thus observed to not need too much time in confirming the occurrence, or non-occurrence, of the sag. The different voltage amplitudes of the voltage sags are also significant at 9° phase angle. Therefore, information at 9° is sufficient to indicate voltage sag.

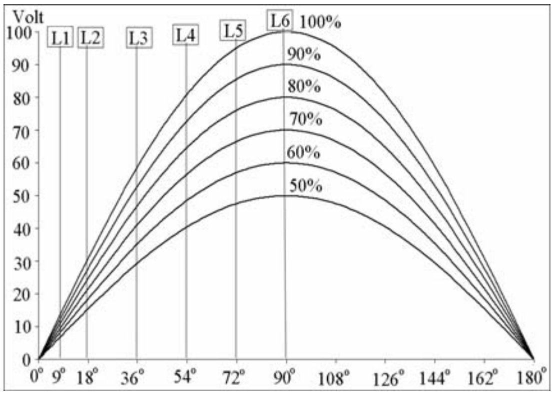


Fig. 5: Half cycle of a sinusoidal at various voltage amplitudes

Based on that, a new voltage-sag detection technique based on phase angle analysis is hereby introduced. It offers immediate detection and compensation of voltage sag. In other words, the new technique can detect and compensate sag the moment it occurs.

Determination of voltage amplitude is done by using [10],

$$V(k) = V_m \sin(kw\Delta T) \qquad (1)$$

where $V(k)$ is voltage at sample k, V_m is peak voltage, k is sample in digital operation, w is fundamental frequency, and ΔT is sampling time.

For example, if sampling rate for one cycle of sinusoidal waveform is k =200, fundamental frequency is set at 50Hz and V_m =100V, then sampling time is calculated as,

$$\Delta T = \frac{20\times 10^{-3}}{200} = 100\mu s \qquad (2)$$

Magnitude of normal voltage at 5th sample, equivalent to 9° phase angle, is calculated as follows:

$$V(5) = 100\sin[(5)(2\pi)(50)(100\mu)] \quad (3)$$
$$= 15.64V \quad (4)$$

If allowable voltage drop is less than 10%, therefore voltage sag must be compensated if it drops to below 14.076V. Let’s now calculate the magnitude of 70% voltage sag at the 5th sample (9°), where $Vm = 70V$,

$$V(5) = 70\sin[(5)(2\pi)(50)(100\mu)]$$
$$= 10.95V \quad (5)$$

If (5) is compared with (4), the following is found:

$$\frac{15.64 - 10.95}{15.64} \times 100\% = 30\%$$

meaning a voltage drop to 30% of rated voltage. This value is still the same with the percentage of voltage drop calculated at 90° phase angle.

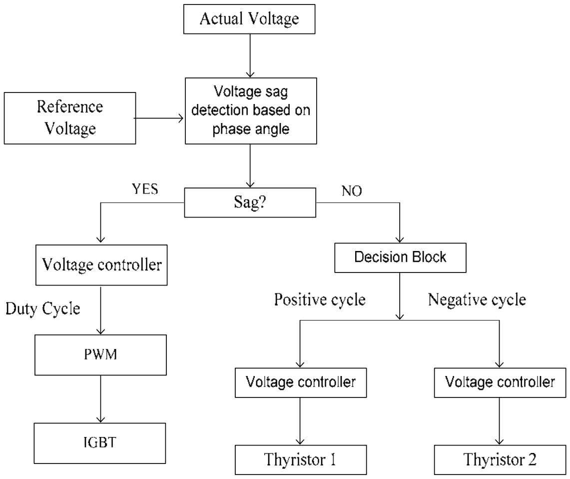


Fig. 6: Flowchart of the New Voltage Sag Detection technique

This technique has less computational compared with other techniques. Figure 6 shows the process of the new voltage sag detection technique. Actual voltage is compared with reference voltage, done by voltage-sag detection based on phase-angle analysis, to determine whether sag occurs or not. If there is no voltage sag, the decision block will split the waveform into positive and negative cycles. Gate signals for thyristor 1 and thyristor 2 are then generated and at the same time turning OFF the IGBT.If voltage sag is detected, the voltage controller generates duty cycles and PWM signals according to sag severity. At this moment, thyristors 1 and 2 are being turned off.

4. PHASE ANGLE ANALYSIS AGAINST OTHER VOLTAGE SAG DETECTION TECHNIQUES

Figure 2(b) depicts the duration needed by RMS Value Evaluation technique in detecting ideal 50% voltage sag. Obviously, the rms curve drops from 1p.u. value to 0.5 p.u. value in one cycle. In other words, this technique needs one cycle to detect voltage sag from the moment sag occurs or detection time is delayed by one cycle. Peak Value Evaluation technique has improved the one cycle delay time shown by RMS Value Evaluation technique by reducing the delay time to quarter a cycle as shown is Figure 4.

Based on Phase Angle Analysis technique, the voltage drop percentage, for instance 50% sag, at any phase angle is the same as described before. Therefore, the voltage drop can be detected immediately as shown in Figure 7.

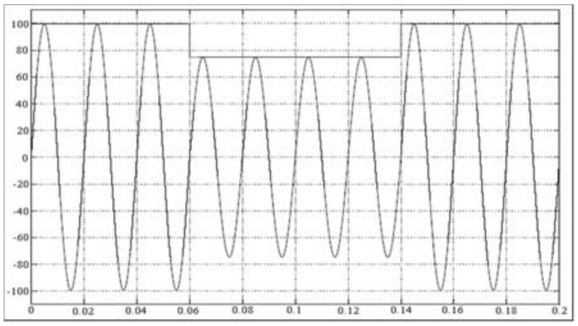


Fig. 7: Duty cycle of the proposed voltage sag detection technique and V_{input} (50% of sag) vs time

Figure 7 shows the input voltage waveform and the sag detection curve of the Phase Angle Analysis technique when voltage dropped to 50% of rated voltage. The sag was observed to be detectable immediately at the beginning of the first sag cycle and ends the moment sag disappears. Figure 7 can be used to see the waveform’s real-time variation from the ideal, and the sag’s actual severity. It indicates the duration of sag, as well as the start and the end of the sag.

5. VOLTAGE SAG COMPENSATOR

In this work, the single-phase voltage-sag compensator proposed in [11] is used as reference when developing the three-phase voltage-sag compensator; see Fig. 8. It comprises two thyristor bypass switches, one PWM insulated-gate bipolar transistor (IGBT) switch in bridge configuration, two output filters, and an autotransformer. The output filters comprise a notch filter and a capacitive low-pass filter, to reduce the output voltage's harmonic components to less than 5% THD as required in a power system. The compensator works for only a few seconds and remains in off-state most of its operation time. Its working principle can be described as follows; in normal conditions, the bypass switches (Thyristors 1 and 2) remain ON. If the sensing circuit detects more than 10% voltage sag, the bypass switches are turned OFF by the voltage controller, which, at the same time, commands the IGBT to start PWM switching so the output voltage is regulated and compensated back to normal voltage. Once the input voltage has no more sag or less than 10% sag, the voltage controller commands the IGBT to turn OFF, turning the thyristor ON. To suppress peak voltage during turn OFF, an RC snubber is used at every switch, so current diverts to the snubber and the energy stored in the current path is dumped into the snubber capacitor every time those switches are turned OFF. Here, an autotransformer of ratio N1:N2 = 1:1 is used to boost up to 50% voltage sag.

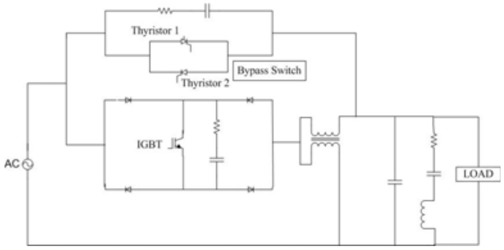


Fig. 8: Single-phase voltage-sag compensator

Figure 9 is the developed three-phase voltage-sag-compensator configuration. Simulation results show the compensator produces the best output without filters. The low-pass filter and the notch filter explained were thus discarded from the simulation.

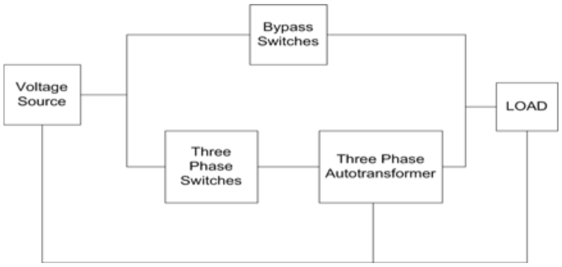


Fig. 9: Three-phase voltage-sag compensator without filters

6. RESULTS AND DISCUSSION

MATLAB/Simulink was used. Figure 10 is the three phase compensator's simulation block. RC-snubber values used for the bypass switches were R=100Ω and C=1nF, and for the IGBT, R=7Ω and C=20µF. As mentioned, the three-phase compensator differs from the single-phase compensator of [11] in the filters. IGBT switching frequency used for the PWM switch was 1.5kHz. Sag simulated was 50%, lasting 4 cycles (equalling 0.08s) for single phase sag and three phase sag. To validate the effectiveness of the proposed sag detection technique in detecting and compensating sag the moment sag occur, voltage sag at different phase angle were simulated.

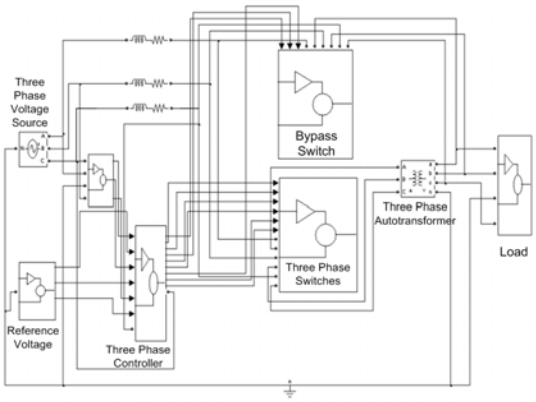


Fig. 10: Simulation block of the three-phase PWM-switch autotransformer voltage-sag compensator

Figure 11 is the 100V peak value of a three-phase input-voltage with only one phase (phase A), dropped to 50% rated voltage at 0º phase angle. The sag is well regulated to the normal voltage immediately as shown in Figure 12.

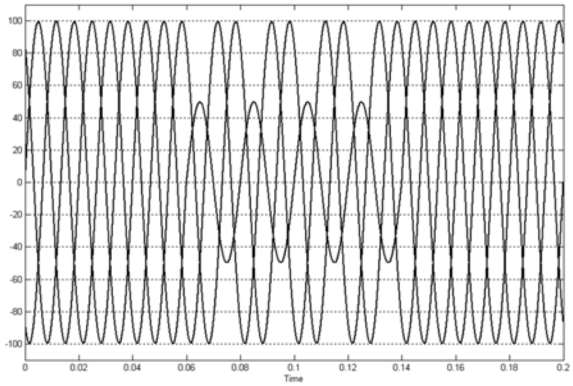


Fig. 11: Single-phase voltage sag (50%) vs. time at 0º phase angle

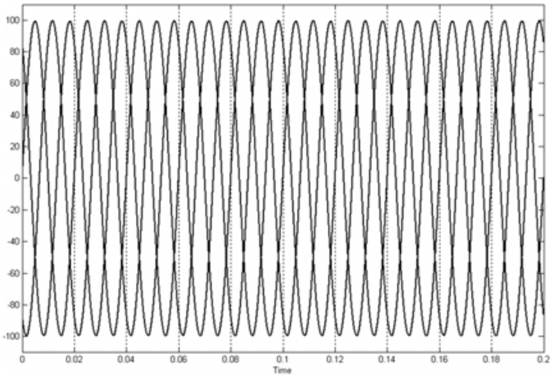


Fig. 12: Compensated output voltage for single-phase voltage sag at 0º phase angle.

Figure 13 shows another sag condition: three-phase sag occurring simultaneously where the phase A sags at 0º, phase B sags at 240º and phase C sags at 120º phase angle.

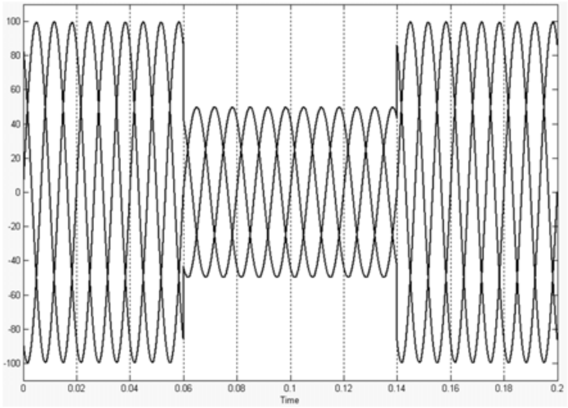


Fig. 13: Three-phase voltage sag (50%) vs. time

The simulation result shown in Figure 14 depicts the three phase sag was effortlessly re-regulated to the desired 100V with non disturbance in the output voltage signal. It also shows that the proposed detection technique may compensate sag the moment it occurs at any phase angle.

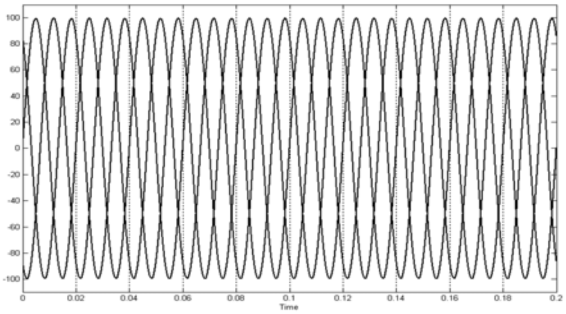


Fig. 14: Compensated output voltage of the three-phase voltage sag

To validate the working principle of the controller, Figure 15 is presented. Figure 15 shows the generated gate signals for IGBT of the three phase compensator when three phase voltage sag occurs. The gate signals are generated immediately once the detection circuit detects voltage sag occurrence at any phase angle. The result show that voltage sag can be detected and compensated the moment sag occurs. There is no delay and no difficulties in detecting voltage sag as well as no disturbances in the output voltage waveform.

7. CONCLUSION

The simulation of the three-phase PWM-switched autotransformer voltage-sag compensator that uses the proposed Phase Angle Analysis technique has been presented. The new technique offers immediate detection and compensation of voltage sag, overcoming the problem of delay in detection time shown by other detection techniques. The proposed detection technique is then applied on three-phase PWM-switched autotransformer voltage-sag compensator. Combination of both proposed detection technique and the three phase sag compensator produce well regulated output voltage. Simulation results show the gate signals were generated immediately and the output voltage was compensated to normal voltage the moment sag occurs, without any disturbances to the output-voltage signal. Voltage-sag detection based on phase-angle analysis can also be used to see a waveform's real-time variation from the ideal, and the sag's actual severity. It can indicate more accurately the duration of sag, as well as the start and the end of sag.

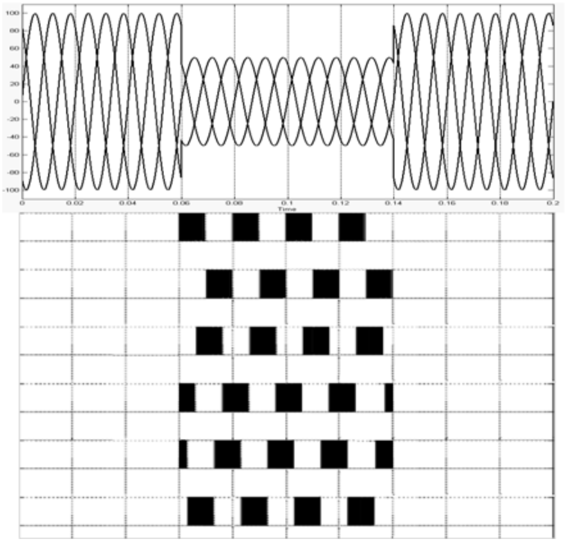


Fig. 15: Input voltage and gate signals for IGBT for three phase voltage sag.

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