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Design and Fabrication of LV Sag/Swell Generator for CBEMA/ITI Compliance Testing

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Abstract- Voltage sag and swell is generated during fault on power system, which trips sensitive equipment. Solar PV and wind turbines voltage changes due to changing of solar radiation and wind velocity respectively. Equipments used in control circuitry can cause to trip or miss-operate. The equipment sensitivity depends on voltage magnitude and duration. This paper presents the designed low voltage sags and swell generator (LVSSG) is used in laboratory to generate power quality problems to evaluate the control equipments sensitivity and to verify CBEMA/ITI/SEMI curves. Voltage sags and swell generator is microcontroller based low cost and portable test equipment. The voltage is controlled through AC chopper from 0 p.u to 1.8 p.u. The normal voltage of sag and swell generator is 1 p.u or 220VAC.

Index Terms: Power Quality, Voltage Sag/Swell, Interruption, VSG Topologies, AC Chopper VSG, CBEMA/SEMI and Low Voltage Ride through (LVRT).

1- INTRODUCTION

POWER quality Power quality determines the satisfaction of power system operation and utilization. Power quality problems are related to voltage, current and frequency that may cause to miss operate or affect utility and customer equipments. Some typical power quality problems are transients, harmonics, distortion, voltage sag, voltage swell, interruption and flickering. The utility and customer both are responsible to mitigate these problems to maintain level of power fitness and continuity. [1],[2] A voltage sag is a short-duration (from 10 m sec to 1 minute) reduction in RMS voltage caused by faults on the power system and the starting of heavy loads, such as starting of industrial process and large size motors. A voltage swell is a short-duration (from 10 m sec to 1 minute) increase in RMS voltage caused by faults on the power system lightening, switching on/off capacitor and suddenly tripping of heavy load Typically the magnitude (in RMS) of voltage sag is 0.9 to 0.1 per unit and the magnitude of voltage swell is 1.1 to 1.8 per unit [3],[4].

Most reasons of voltage sag, swell and interruption are the faults in transmission lines. Some faults in distribution system also occur and this will affect mostly its own or parallel feeders. Main causes of faults are wind and ice effect, animal contact, support structure damage, insulation weak, variation of power system parameters i.e. resonance effect. Some common typical faults which generate voltage sag/swell and interruption are single line to ground (SLG), blowing of fuse on primary side of transformer, capacitor bank and power transformer energizing, starting of heavy induction motor, sudden load tripping and lighting. Voltage sag/swell and interruption can affect power system machines, lightings, process and control equipments i.e. adjustable speed drives contactors and relay, PLC, PID and personal computers (PC). [21], [22],[23],[24]

In 1983 a standard was proposed for personal computers voltage acceptability curve named CBEMA. The voltage acceptability curve CBEMA was revised and remand ITI curve, in 1995. Another curve similar to ITI curve for semiconductor processing equipment known as SEMI F47 was proposed currently. It specifies voltage acceptability with duration from 50 m sec up to 1sec. [21],[22]

Personal computer does not switch off during voltage sag for 5 to 10 milli seconds. However it

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stops the operations perform by the computers and can block of its operating system. PC can malfunction for voltage sag of 75% of its nominal voltage for 80 m seconds. Files corruption, failure of read write operation, CD-ROM initiation, slow down of the network traffic, hard drive and PCI cards can be damaged. Personal computer does not switch off during voltage sag for 5 to 10 milli seconds. However it stops the operation perform by the computer and can block of its operating system. PC can malfunction for voltage sag of 75% of its nominal voltage for 80 m seconds. Files corruption, failure of read write operation, CD-ROM initiation, slow down of the network traffic, hard drive and PCI cards can be damaged. Motor speed is controlled through adjustable speed drive (ASD), with the help of power electronic devices (diodes, transistors and control rectifiers). Protective equipments are used for the protection of these power electronic devices. Adjustable speed drives have transistor driver circuit, input and output control circuit and communication control circuit; which can be easily affected during voltage disturbance. [23],[24],[25]

Products manufacturers are trying to increase productivity, cost reduction, smooth and continuous operation. For this purpose a large number of automatic and intelligent devices i.e. programmable logic controller, proportional integral derivatives, human machine interface and other microprocessor based equipment are used. The speed of operation is very high (in some micro seconds to several nano seconds) a small change in operating voltage may cause to miss operate, function failure or trip. During voltage disturbance programmable logic controller (PLC) stops working, PLC interfaced equipments i.e. transducers and relays also stop working or miss operate; the entire process will disturb due to PLC tripping. High luminous lightings are used in shopping malls, play grounds, wedding halls, restaurants and large scale industries. During voltage interruption and sag these high luminous lightings switch off and then require more time in restoration of its full luminous. High intensity discharge lamp are used in shopping malls, wedding halls, stadiums, factory sites and traffic routers where a lot of people used to get together, the sudden darkness may cause personal injury, life loss or other damages. Emergency lighting system is used in some process industries in most dangerous and heavy moving machineries areas, to avoid accident and miss happening. This emergency lighting system is powered by UPS or other source of power
i.e. a quick start stand by diesel generator. [26-28]

Equipments sensitivity can be checked in two ways; first one is field and second one is laboratory test. The designed sag and swell generator is used in laboratory to test low voltage ride through (LVRT) of equipments. There are several voltage sag generator VSG used for this purpose. In Impedance switching based VSG voltage sag /swell is about 50 % of the nominal, power loss in impedances, harmonics, zero crossing circuit is required for thyristor control reactor, fast switching is required for switching on/off impedance to generate a desire voltage sag for desire duration. Impedance switching based VSG is available in medium size and is very costly. [5],[9],[16] The controlling of full converter (FC) based VSG is complex; generate harmonics, highly costly and not reliability of electronics devices in overvoltage and transients effect in power system. Trouble shooting of inverter and control circuitry is also difficult. [12][16] Transformer based voltage sag generator has fewer numbers of tapping points. Solid state bidirectional switches are used to change the transformer tap position quickly. These bidirectional fast switches are affected by transient and surges produce during switching of tap. Electromechanical based switches are reliable but its operation is slower than solid state bidirectional switches. Transformer based VSG available in medium and large size and very costly. [7],[10],[12]

In AC generator based VSG, generated voltage sag is symmetrical and voltage controlling is simple. These generators are available in medium size and are costly, more maintenance, produces sound and vibration effect. Matrix convertor (MC) MC based VSG has complex control circuit, troubleshooting of control circuit is difficult, input/output filters required, which makes the generator complex and costly. [12] AC chopper based VSG, has easy control circuit, low maintenance, low cost, no sound and vibration effect, single/three phase VSG, all types of voltage sag, voltage swell and interruption. These generators have small size of output filters, low harmonic contents and better power factor (p.f). [9],[19]

2- OVERVIEW OF DIFFERENT SAGS AND SWELL GENERATORS (VSG)

2.1 Impedance switching VSG

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There are two impedances in this circuit, series impedance Z_S and shunt impedance Z_{SH}. The impedance switching produces a voltage drop across series impedance. The voltage across series impedance can be controlled by controlling the current of shunt impedance. The current flowing in series impedance will produce a voltage drop and the voltage at point of common coupling will obviously reduce.[5][9]

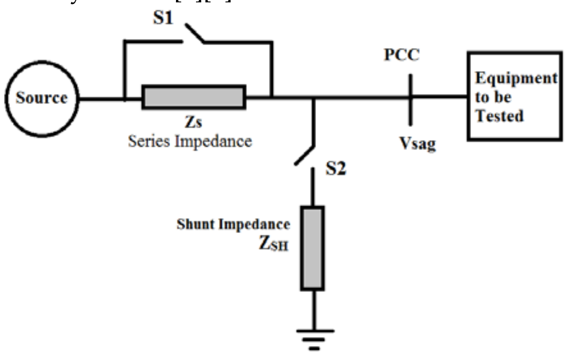

Fig. 1 Impedance switching VSG

$$V\ sag = V_{source}\left(\frac{Z_{SH}}{Z_{SH}+Z_S}\right) \quad (v) \qquad (1)$$

These impedance are Inductance (L), Capacitance (C) and Resistance (R), series and paralle combination of RLC. Thyristor Control Reactor (TCR), fixed Capacitor and Thyristor Control Reactor (FC-TCR). In TCR Inductive reactance can be controlled by controlling the firing angle of thyristor. Circuit breakers, magnetic contactors and solid state bidirectional switches can be used for switching on/off S1 and S2. Circuit breakers and magnetic contactors are used for few numbers of impedance switching, while thyristors and IGBT based switching are fully controlled. [6][12-13]

$$v_s(t) = V_s Cos\omega t \qquad (2)$$

$$i(t) = \frac{1}{L_c}\int_0^{\pi/2} v(t)dt = \frac{V_s}{\omega L_c}(Sin\omega t - Sin\alpha) \qquad (3)$$

$$i(t) = \frac{1}{L_c}\int_0^{\omega t} v(t)dt = \frac{V_s}{\omega L_c}(Sin\omega t - Sin\alpha) \qquad (4)$$

Thyristor based voltage controlling has zero crossing, harmonics and filtering issues. IGBTs are used to fully control the voltage and have fast switching on off capacity. Three phase switch S1 is simultaneously turned on or off, while three phases switching S2 are independent to turn on off to produce single, two or three phase voltage sag. There is no voltage swell and interruption in this impedance switching based VSG. The switching S1 and S2 on off also produce an over current. For example, it requires 2.2 times apparent power of load if we want to generate 50% sag voltage.[8],[9],[16]

2.2 Full Scale Convertor or Back-to-Back Convertor

This type of voltage sag generator consists of rectifier to convert AC voltage into DC voltage; an inverter is used to convert this DC voltage back into controllable AC. The controlling of inverter is complex; generate harmonics, highly costly and not reliability of electronics devices in overvoltage and transients produce in power system. The DC link voltage is also not enough to produce a voltage swell.[9],[12],[16]

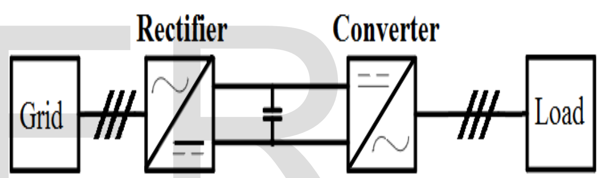

Fig. 2 Full convertor voltage sag generator

2.3 Transformer Based VSG

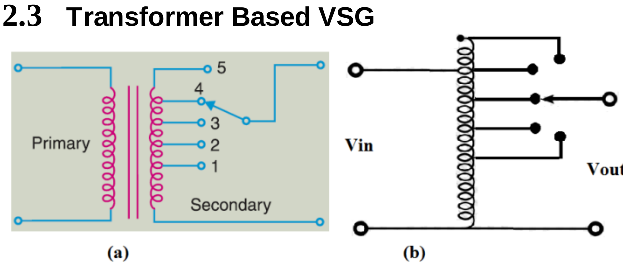

Fig. 3 (a) Multiple tap transformer
(b) Autotransformer

Transformer based voltage sag generator has fewer numbers of tapping points. Isolation transformer with multiple tap (a) and the autotransformer (b) with multiple tapping points are used to control voltage. Solid state bidirectional switches are used to change the transformer tap position quickly. These bidirectional fast switches are affected by transient and surges produce during switching of tap.

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Electromechanical based switches are reliable but its operation is slower than solid state bidirectional switches. [7][10][12][16]

$$V\ sag\ =\ K \times V_{input}\quad (V) \qquad (5)$$

K = N2/N1 (Transformation Ratio)

Solid State Relay (SSR) And Variac Based VSG

The SSR (solid state relay, a semiconductor power module), variable resistance and variable transformer (variac) based VSG is used for three-phase balanced/unbalanced voltage sags. This SSR based VSG is can also be used a series active filter power quality conditioner. This SSR based VSG is consists of three SSR controlled parallel paths per phase as shown in Fig.4 and it is inserted between the voltage source and the load in series. Each phase consists of three SSRs, a variable resistor, and a variable transformer. The SSRs line provides the nominal voltage and the line involving the variac and the switch SSRv provides the pre-set sag voltage to the load for as long a duration as intended. [7],[11]

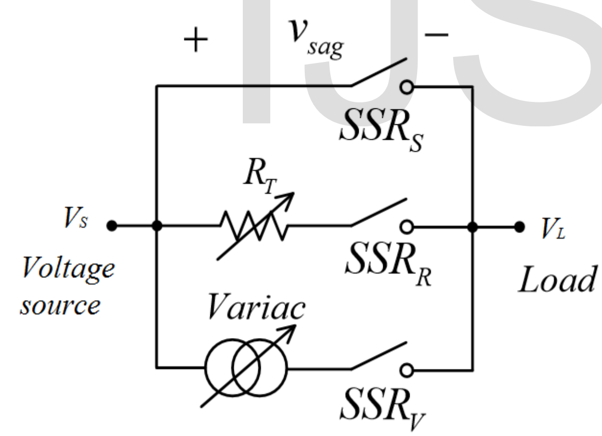

Fig.4 Solid State Relay (SSR) based VSG

2.4 Generator based VSG

The generator based VSG voltage can be control by controlling DC excitation voltage and field current. To control DC excitation voltage, DC chopper with controllable PWM is required. DC voltage can also be controlled by using fixed resistors with multiple tap. The generated voltage sag will symmetrical voltage sag, voltage controlling is simple. [12]

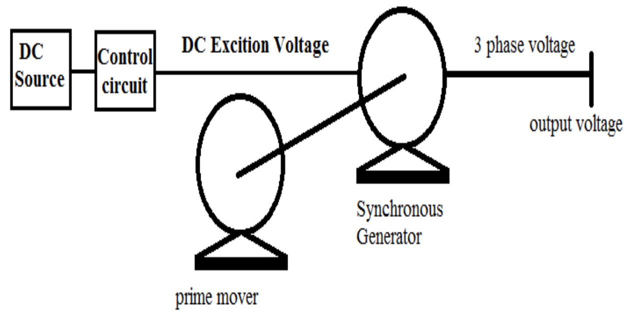

Fig. 5 Generator based VSG

2.5 Matrix Converter (MC) based VSG

A 3-phase 4-leg MC has 12 switches distributed as shown in Fig. 6. The inputs voltage are designed by the capital font "A", "B" and "C" while the output voltages designed by the lower case font " a", "b", "c" and "d". Representing each switch state of the MC with a 1 logic state for close operation and with a 0 logic for open operation, it is possible to obtain at the output any input voltage. The Table 1 shows a combination of switching states to obtain "A" input voltage at "a" output voltage, "B" input voltage at "b" output voltage and "C" input voltage at "c" output voltage. [12]MC based VSG has complex control circuit, troubleshooting of control circuit is difficult, input/output filters required, which makes the generator complex and costly. [16]

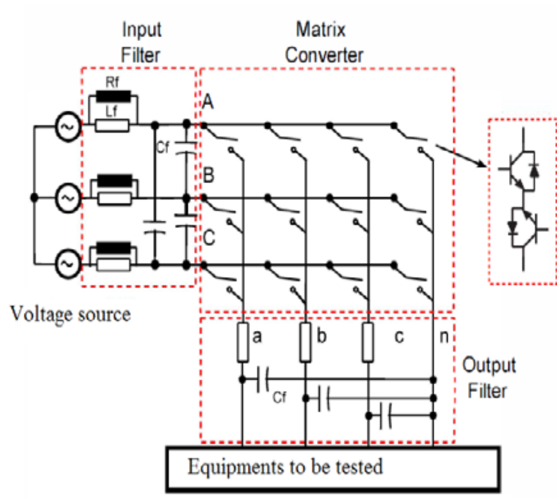

Fig.6 Matrix converter based VSG

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Table.2 Comparison of different VSG [16]

VSG Type	Control	Recovery Profile	Fault Type	Maintenance	Size
Impedance based VSG	Easy	Difficult	Some	Easy, Cheap	Medium
Transformer based VSG	Easy	Difficult	3 Phase, Symmetrical	Easy, Cheap	Medium
Full Converter	Complicated	Easy	All Types	Difficult, Costly	Small
Matrix Converter	Complicated	Difficult	All Types	Difficult, Costly	Medium
Generator based VSG	Easy	Difficult	3 Phase, Symmetrical	Difficult, Costly	Medium
AC Chopper based VSG	Easy	Easy	All Types	Easy, Cheap	Small

TABLE 1 Matrix Converter Output Voltage

INPUT	A	1	0	0	0
	B	0	1	0	0
	C	0	0	1	0
OUTPUT		a	b	c	n

2.6 AC Chopper Based VSG

Recently, the studies of AC chopper for ac voltage control has been increased because it has many advantages such as high input power factor, sinusoidal output voltage with small low-pass filter requirement and fast response. S1 and S2 are bidirectional switches (IGBTs/MOSFET) as shown in Fig.8. In nominal condition S1 is closed, to generate voltage sag the S1 can be turn on and off to control the voltage. Theses switches are operated very fast. The duty cycle of PWM signal for S1 can be controlled for desire voltage sag. T2 is a step up transformer and used for voltage swell. To generate voltage swell S2 can be turn on and off to control the voltage while S1 should be turn off completely for voltage swell period. The duty cycle of PWM signal for S2 can be controlled for desire voltage swell. Thus voltage sag or swell will be generated at PCC. [9]

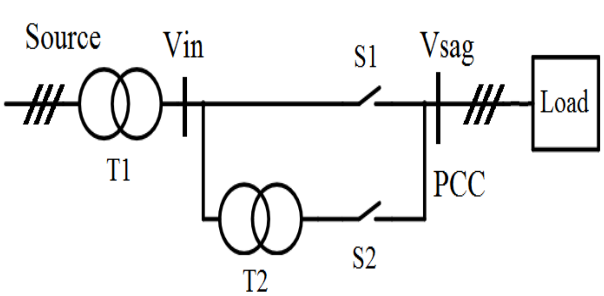

Fig. 7 AC Chopper based VSG

3 AC CHOPPER TOPOLOGIES

3.1 Full Bridge Bidirectional Switch

This circuit contains only single transistor as shown in Fig. 9. If gate pulse is available on the gate of IGBT Q1, during the positive half cycle the D1, Q1 and D4 will conduct, during the negative half cycle D3, Q1 and D2 will conduct.[9] [19][20]

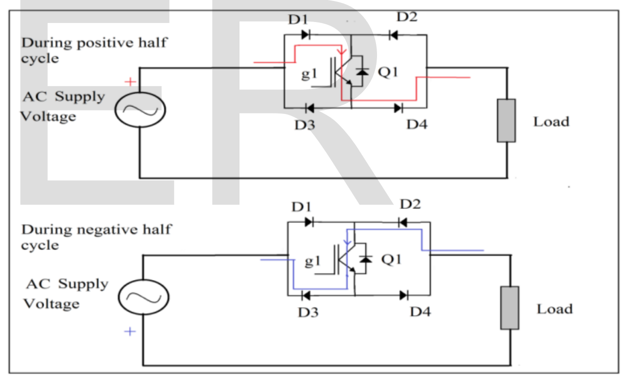

Fig.8 Full bridge bidirectional switch

3.2 Anti -parallel Connected IGBTs Circuit

This circuit consist of two transistor connected in anti parallel as shown in Fig. 10. If gate pulses are available on the gate of IGBT Q1 and Q2, during the positive half cycle of power supply frequency D1, Q1 and D2 will conduct and D3, Q2 and D4 will not conduct, similarly during the negative half cycle of power supply frequency the D3, Q2 and D4 will conduct and D1, Q1 and D2 will not conduct.[14][15]

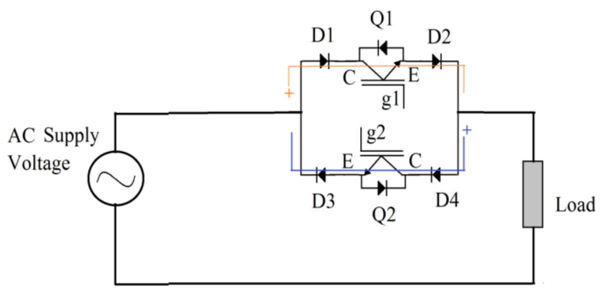

Fig.9 Switches are connected in anti parallel

3.3 Inverse Series Connected IGBTs Circuit

In this circuit two IGBTs are used with common emitters, one collector of one IGBT is used for AC input and the collector of second IGBT is used as AC output (Fig. 11). During positive half cycle of input power supply the transistor Q1 will conduct from collector to common point of emitters, from common point of emitters the Q2 will not conduct but the built-in diode in Q2 will conduct to collector side, similarly during negative half cycle Q1 will not conduct but the built-in diode in Q1 will conduct to common point of emitters and from emitter of Q2 to collector.[14]

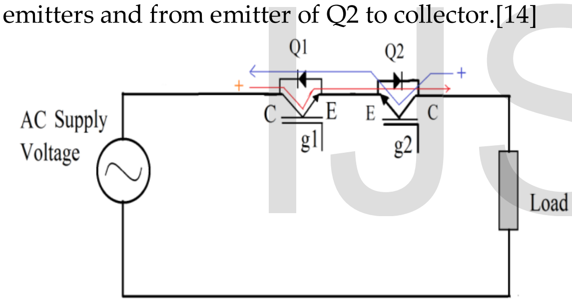

Fig.10 series connected bidirectional switch

The PWM pulses on IGBTs gate may be single pulse or multiple pulses. Single PWM pulse is given to IGBT during each half cycle of power frequency.

Multiple PWM pulses are given to IGBT gate during each half cycle of power frequency to cut some portions of input sine wave. The chopping in sinusoidal wave form can be control by controlling the PWM percentage of duty cycle of gate pulse.

$$Vs = VmSin\omega t \tag{6}$$

$$Vrms = \frac{Vm}{\sqrt{2}} \tag{7}$$

$$Vrms = D * \frac{Vm}{\sqrt{2}} \tag{8}$$

Vm= peak voltage, D= PWM duty cycle (%)[17-18]

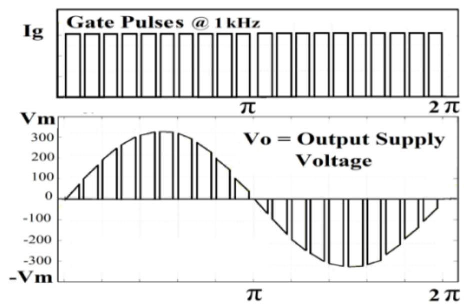

Fig .11 Multiple PWM pulses with 75% duty cycle and the output of AC Chopper

4 DESIGN OF VOLTAGE SAG AND SWELL GENERATOR

The designed voltage sag and swell generator (VSSG) is based on AC chopper, series connected IGBTs and step up transformer 220/400VAC. AC chopper is used to control voltage from 0-200% by controlling PWM duty cycle (0-100%). Thus voltage sag, swell and interruption can be generated for testing of equipment.

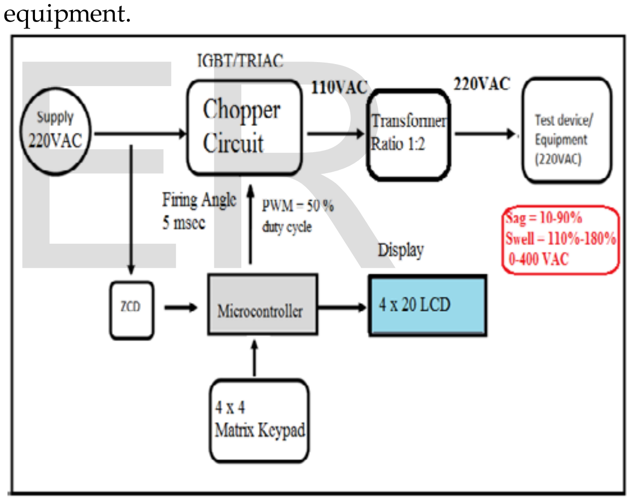

Fig.12 Block diagram of VSSG

Transformer is used to convert 220 VAC into 400 VAC. To generate voltage sag, input values to controller (ATMEGA2560) through keypad should be 10% - 90%. Similarly to generate voltage swell, input values to controller through keypad should be 110% - 180%. 4 x 4 matrix keypad is used for entering the value of voltage magnitude in percent and duration in milliseconds. A 20 x 4 character LCD is used to display data which can be entered to microcontroller through keypad. LCD can be operated in 4 bit mode and 8 bit mode, here LCD is used into 4 bit mode. 4 pins and signals are used to transfer data from controller to LCD for displaying.

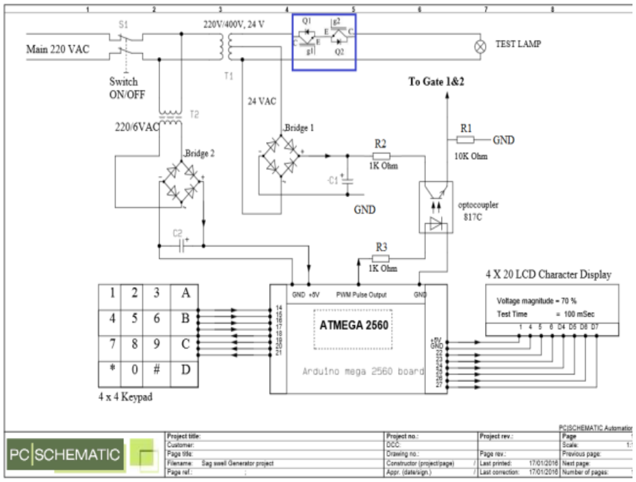

Fig.13 Schematic Diagram of VSSG

Fig. 14 View of VSSG

Fig. 15 chopper circuit output @ 20 kHz PWM frequency

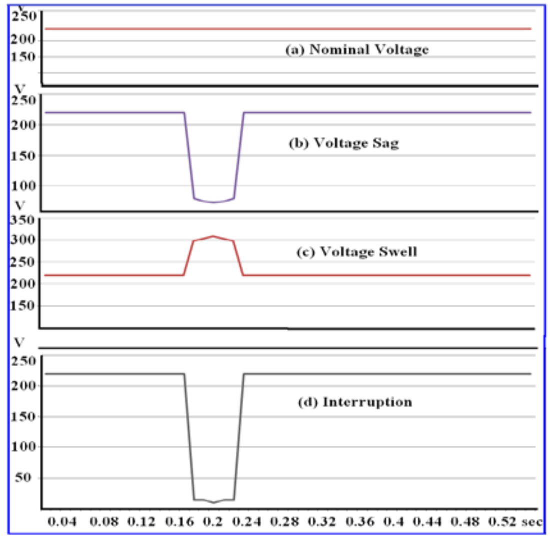

Fig.16 Output RMS voltage of sag and swell generator (a) Nominal voltage (b) voltage sag (c) voltage swell (d) voltage interruption

5 SIMULATION

5.1 Simulation of Voltage Sag Due to SLG Fault

The voltage source block consist of voltage value of 11 kV and frequency and phase shift parameters. The block of power transformer has parameters; 500 kVA power rating, 11kV/400V line to line RMS voltage, winding connection is delta to star (Δ/Y ungrounded).

A block of three phase fault is used to inject fault in power system. Single line to ground, double lines to ground and three lines to ground fault, with ground resistance, and fault duration are the parameters used in this block. The magnitude of fault current depends on ground resistance or the magnitude of voltage sag depends on ground resistance.

A single line to ground fault for duration of 0.2 seconds with ground resistance of 1 Ohms, is injected in power system on the primary side (delta connected) of transformer, the voltage sag is observed in two lines on secondary side (star connected).

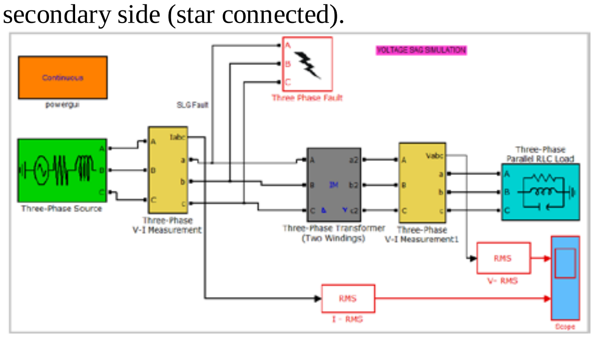

Fig.17 MATLAB Simulation of voltage sag due to SLG fault

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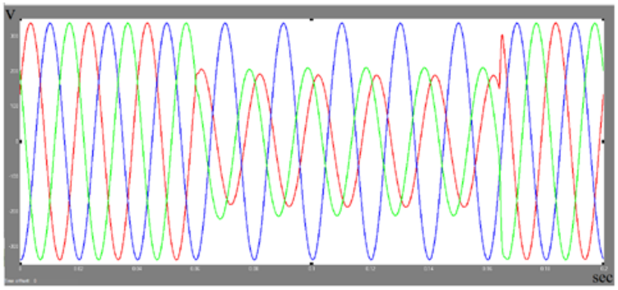

Fig.18 Transformer secondary voltage wave form due to SLG fault on primary side for duration of 10 cycles (50Hz) or 0.2sec (for Δ/Y ungrounded connection)

5.2 Simulation of AC Chopper Voltage Control

AC chopper consists of two transistors (IGBTs) and two diodes which are connected in anti parallel. A PWM of 1 kHz signal is provided to the gate of both IGBTs. The output voltage can be controlled by increasing and decreasing the percentage of duty cycle of the PWM generator block. The scope block is connected to check the input voltage, chopped AC wave form at the output of transistors. The RMS block is used to check the input RMS voltage and output RMS voltage, after chopper circuit the RMS output voltage is decreasing as decreasing the percentage of duty cycle and vice versa. Another AC chopper with series connected IGBTs (opposite polarity) is used in MATLAB simulation as shown in Fig.21.

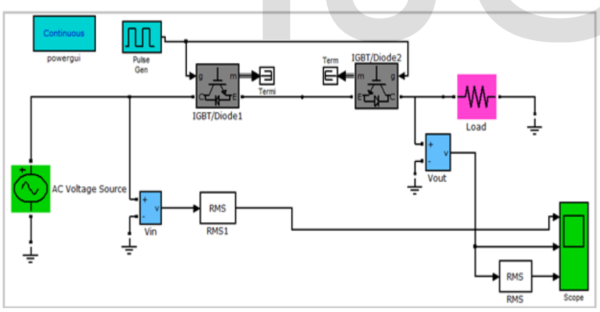

Fig.19 AC chopper with anti-parallel connected IGBTs in MATLAB Simulink

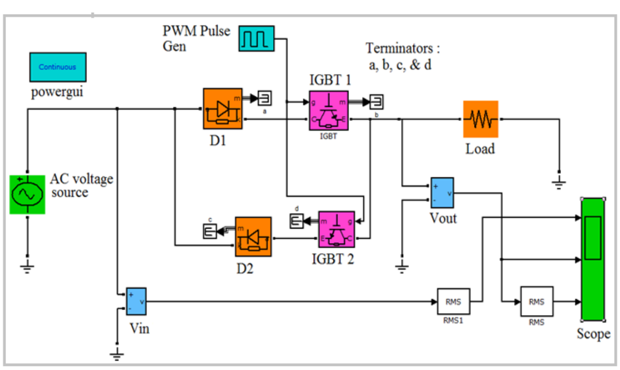

Fig.20 AC chopper with anti-parallel connected IGBTs in MATLAB simulink

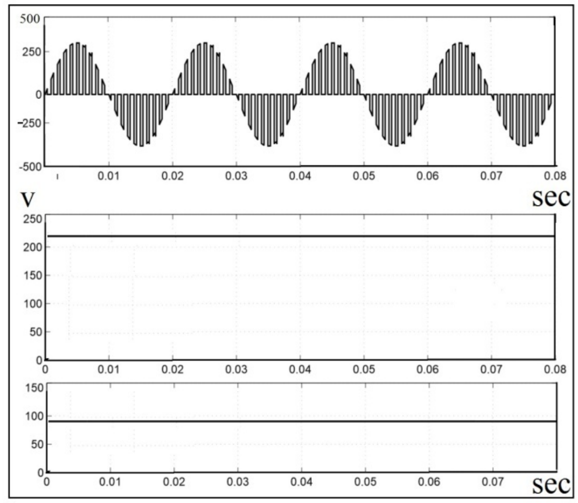

Fig.21 Output chopped wave form at 50% duty cycle for anti parallel and series connected IGBTs.

6 Conclusion

Currently a lot of AC chopper circuits are used in many industrial applications. IGBTs are prefer over thyristors due to fast switching, low harmonics and small size of filter is required for filtering of output voltage. Designed VSSG is portable test equipment, small size of AC chopper and the control of AC chopper circuit is also easy. This paper will also help to design 3 phase AC Chopper circuit to generate all types of voltage sags.

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