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# PSCAD ANALYSIS OF VOLTAGE SAG MITIGATION BY PWM SWITCHING AUTO TRANSFORMER TO IMPROVE POWER QUALITY

Kalappagari Nagendra [1], Y.Damodharam [2], Vusirika Prasad Reddy[3],V.Sekhar[4], A.Arulprakash[5]

[1] PG scholar, Kuppam Engineering college,Kuppam, Andhra Pradesh, India

[2&4]Associate Professor,Kuppam Engineering college,Kuppam, Andhra Pradesh,India

[3] Senior Engineer-Projects Co-ordinator, BHEL EPD ,Bangalore , Karnataka, India

& NIT Scholar, M.Tech Warangal, Andhra Pradesh, India

[5]Associate Professor& Head of Department, Kuppam Engineering College, Kuppam, Andhra Pradesh, India

***Abstract*—This paper deals with the Analysis of a Auto transformer & PWM Technique aimed at examining its capability in improving power quality in a industrial systems. The model comprises of IGBT for switching and Auto transformer as voltage compensator which are connected in series and in shunt to the system. A generalized sinusoidal pulse width modulation switching technique is developed in the proposed controller design for fast control action of the compensation. Analysis was carried out using the PSCAD/EMTDC electromagnetic transient program to validate the performance of the Compensation model. Analysis results verify the capabilities in performing voltage sag compensation, flicker reduction, voltage unbalance mitigation, UPS mode, power-flow control and harmonics elimination. A comparison of the this device with other custom power devices shows that the ATAPWM gives a better performance in power-quality mitigation.**

***Index Terms*—Power-quality mitigation, IGBT, Auto transformer, PWM Technique.**

## 1.1 Introduction:-

The World is moving towards provide Continuous power with quality. In order to supply such quality power our Engineering persons did so many experiments since 18th Century. The world having so many power quality revolutions step by step such a way improve power quality aim, Saving power 1kWH at customer end is equal to generation power at 15-20kWH.The term “power quality” means different things to different people. One definition is the relative frequency and severity of deviations in the incoming power supplied to electrical equipment from the steady 50 Hz, sinusoidal waveform of voltage or current.

These deviations may affect the safe or reliable operation of equipment such as computers, Automation equipments, Drive control Desks, Console desk panel, SCADA,DCS Controlling system of Power Control center& Motor Control center. The poor power quality happens by Voltage sag & swells. These causes serious interruption at Up-Stream breaker and also Down-Stream breakers so our entire plant goes to shut down state The Auxiliary power supply failure automatically our Main power also failure by Breakers trip signals generated by protective relays.

This Protective relays sometimes produces mal trip signal by Voltage sag & Voltage swells like under voltage trip signal, over voltage trip signal similarly current signals also come to picture.

The Voltage sag & swells can define also long interruption or short interruption based on voltage magnitude and Time period of same signal. if The small period signal interrupt our Large Thermal Power Station, again it take 8hr to 1Day time to come to stable operation condition, Let us take Ex: Rayalasima Thermal Power station Generating capacity 5X250 MW, If this much huge Generation plant go to Shut down state think loss of Power & Unit price. At this time End user receives Poor Power.

## 2.1Test Cases and Simulation Results

### Test Case I: Voltage sags analysis for 9-bus industrial system with four Induction motor as a load

The industrial distribution system considered is a 9-bus system with four Induction motors as loads and its PSCAD/EMTDC model is shown in Fig. 2.21[6]. System data have been taken from [6] , whose details are as follows

- Source voltage = 14.55 KV
- Source impedance= 0.0066+j 0.0525 p.u
- Base power = 10MVA
- Base voltages for three levels are 13.8K.V, 4.16 K.V , 1.1K.V

Transformer and feeder data for the test system is given in table 2.4 and motor parameters in table 2.5.

Table 2.1 feeder Parameters

| **Line** | **1-3** | **3-4** | **1-2** | **2-7** | **7-8** | **2-6** | **6-9** | **2-5** | **1-10** |
|---|---|---|---|---|---|---|---|---|---|
| **R(p.u)** | 0.0304 | 0.045 | 0.0042 | 0.0282 | 0.108 | 0.0165 | 0.0681 | 0.06 | 0.0038 |
| **X(p.u)** | 1.1056 | 0.09 | 0.017 | 0.101 | 0.054 | 0.0364 | 0.034 | 0.12 | 0.005 |

Table 2.2 Induction motor parameters

| **Motor** | **M1** | **M2** | **M3** | **M4** |
|---|---|---|---|---|
| **Bus** | 4 | 8 | 9 | 5 |
| **S[KVA]** | 597 | 2712 | 4269 | 3420 |
| **V[KV]** | 4.16 | 1.06 | 1.1 | 4.16 |
| **H[s]** | 0.02 | 0.02 | 0.02 | 0.02 |
| **S(%}** | 2.209 | 2.87 | 3.443 | 2.147 |
| **$R_s$** | 0.0163 | 0.0235 | 0.0235 | 0.0759 |
| **$X_s$** | 0.0816 | 0.1353 | 0.1353 | 0.0759 |
| **$X_m$** | 2.250 | 2.580 | 2.580 | 2.620 |
| **$R_r$** | 0.0287 | 0.044 | 0.044 | 0.0288 |
| **$X_r$** | 0.0836 | 0.143 | 0.143 | 0.1037 |

## 3.1 Basic Voltage sag mitigation Techniques

To mitigation of Voltage sag then installing a proper power conditioning equipment is a common solution for the power quality problems. Power conditioning usually involves voltage conditioning because most power quality problems are voltage quality problems. Most devices are utilized to condition or modify the voltage magnitude or frequency. Power conditioning can be used to condition the source, the transmitter, or the receiver of the power quality problem. The cost of power conditioning solutions is increased from end-user side to utility side. Some common power conditioning equipment that correct voltage sags are given below.

**Line-voltage regulators**: These regulators are transformers specially designed to regulate the output voltage when the input voltage changes. They make changes to keep the output voltage relatively constant. Types of line regulators are: Tap changers, buck-boost regulators, CVT (Constant- voltage transformer).

**M-G Sets (Motor-generator Sets)**: A motor is connected to the utility supply and runs the generator through a shaft or belt, providing clean power to critical equipment. If power is interrupted, the generator keeps supplying power to critical loads by using diesel or natural gas as the fuel. A rechargeable battery pack or a flywheel can be added to M-G Sets to provide power during ride through. Maintenance and safety are the main concern.

**Magnetic Synthesizers**: These regulators employ resonant circuits which are made of nonlinear inductors and capacitors to store energy, pulsating saturation transformers to modify the voltage waveform, and filters to filter out harmonic distortion. They supply power through a zig- zag transformer, which traps triple harmonic currents and prevents them from reaching the power source. They can be bulky and noisy.

**SVC (Static VAR Compensators)**: These regulators utilize a combination of capacitors and reactors to regulate the voltage quickly. They use solid-state switches that insert the capacitors and reactors at the right magnitude to keep the voltage from fluctuating. However they are quite large and expensive.

**UPS (Uninterruptible Power Supplies)**: A UPS conditions the voltage, both during voltage sags and outages. It provides a constant voltage from a static source (battery, ferro resonant transformer, superconducting magnet etc.) or rotary source (diesel motor generator set). The basic building blocks of a UPS system include the battery (with a 5 to 60 minute backup capability depending on its size), an inverter, and a rectifier. They are connected in three different configurations.

i. On-line UPS: Battery backup and continuous sag/swell protection is available all the time. It has a shorter battery life.

ii. Off-line UPS: Time delay of 4-10 milliseconds to engage the UPS during an interruption. It has a longer battery life.

iii. Line interactive UPS: A hybrid of the above two types. It has a shorter time to engage UPS and also saves battery life.

iv. A Rotary UPS module (i.e., a motor-generator set) can be added to the above types to produce a waveform independent of utility voltage and provide a longer backup time during outages.

**SMES (Superconducting magnetic energy storage)**: SMES stores electrical energy within a superconducting magnet. It provides a large amount of power (750 kVA to 500 MVA) for a short time (2 seconds) very quickly (within 2 milliseconds).

**Fuel Cell Based Inverter System**: The main disadvantage is its high cost. Present day modern equipment's are very sensitive to voltage sags and they need the mitigating device to be very fast in acting, which cannot possible by the above conventional devices. So in order to overcome the above disadvantages, a new category of devices called custom power devices are developed. Custom power devices are the new generation of power electronics-based equipment aimed at enhancing the reliability and quality of power flows in low-voltage distribution networks. There are various custom power devices available such as DVR (dynamic voltage restorer), D-STATCOM, and UPQC (Unified Power Quality Conditioner) etc

## 4.1 *Test Cases And Simulation Results*

***Test Case I:*****Voltage sag/swell mitigation using three phase 6-Pulse Distribution Static compensator (DSTATCOM)**

Fig. 3.10 shows the test system implemented in PSCAD/ EMTDC to carry out simulations for the D-STATCOM. The test system comprises a 230 kV transmission system, represented by a Thevenin equivalent, feeding into the primary side of a 3-winding transformer. A varying load is connected to the 11 kV, secondary side of the transformer.The system parameters used for the simulation is given in table3.2

Table 4.1 System parameters used for simulation

| | |
|---|---|
| Supply | 3-Phase100 MVA, 230kV, 50 Hz, a.c supply |
| Injection transformer | Primary: 230kV, 100MVA, 50 Hz<br>Secondary: 11KV ,100 MVA, 50 Hz |
| Load1(sensiive load)<br>Load 2<br>Load3 | R=12.1 L=0.1926/phase<br>R=0.05 L=0.0059/phase<br>C=3uF/phase |
| PI controller gain | 126 |
| $V_{DC}$ | 53 KV |
| Switching frequency | 5KHZ |
| Duty cycle | 50% |
| High pass filter | Qfactor-100,basefreq-50hz,cutoff freq-5KHZ |

DSTATCOM controller uses sinusoidal PWM (SPWM) technique and The aim of thecontrol scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. Since custom power is a relatively low-power application, PWM methods offer a more flexible option than the **fundamental frequency switching (FFS)** methods in FACTS applications. Besides, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses. Fig.3.19 shows the test system and D-STATCOM controller implemented in PSCAD/EMTDC. The D-STATCOM control system exerts voltage angle control as follows: an error signal is obtained by comparing the reference voltage with the RMS voltage measured at the load point. The PI controller processes the error signal and generates the required angle $\delta$ to drive the error to zero. The modulated $V_{control}$signal is compared against a triangular signal (carrier) in order to generate the switching signals for the VSC valves.

The main parameters of the sinusoidal PWM scheme are the amplitude modulation index $M_a$ of signal $V_{control}$, and the frequency modulation index $M_f$ of the triangular signal. The amplitude index $M_a$ is kept fixed at 1 P.U, in order to obtain the highest fundamental voltage component at the controller output. The switching frequency $M_f$ is set at 5 KHz. It should be noted that, in this thesis, balanced network and operating conditions are assumed. The modulating angle is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 240 and 120, respectively. It can be seen in Fig. 3.10 (b) that the control implementation is kept very simple by using only voltage measurements as the feedback variable in the control scheme. The speed of response and robustness of the control scheme are shown in the simulation results.

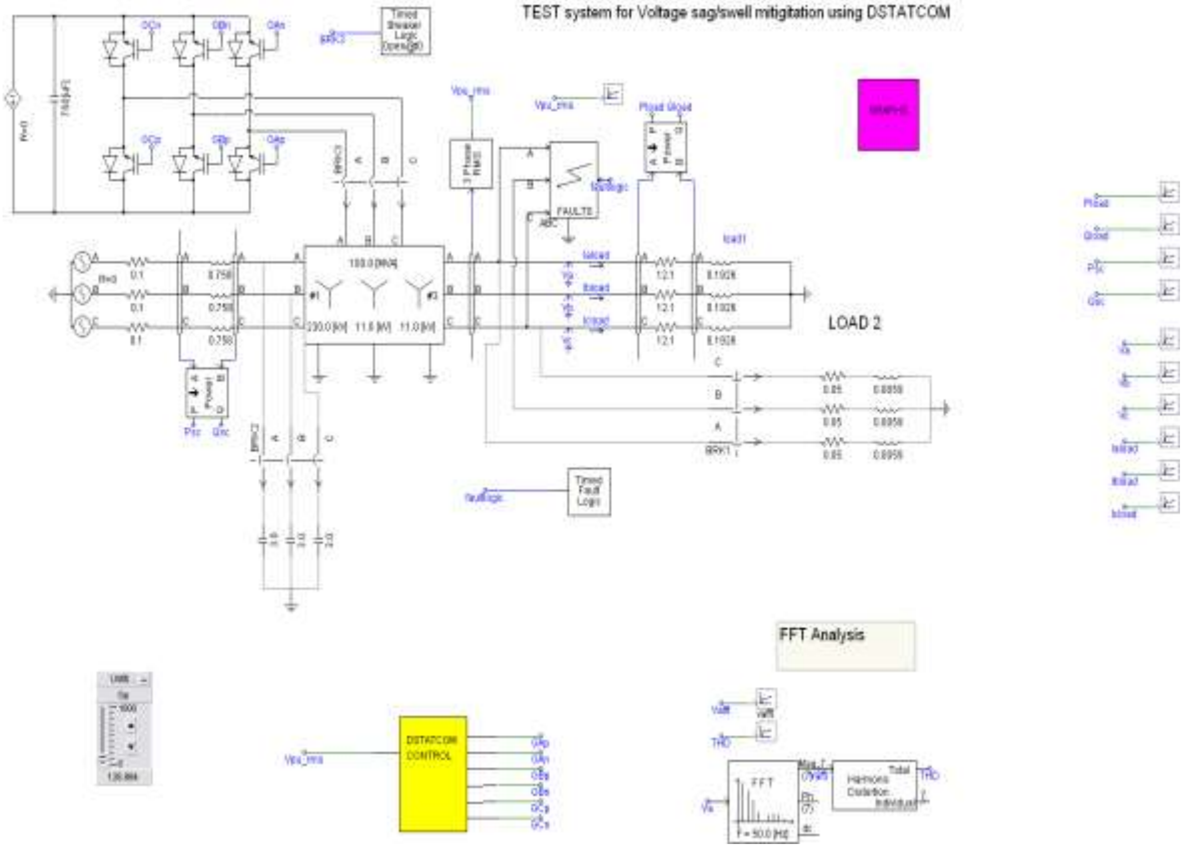


Fig. 4.1 (a) PCSAD/EMTDC model of a three phase 6-Pulse DSTATCOM

## 5.1 Experimental setup at BHEL Engineers training laboratory

The Laboratory setup for the PWM Switching auto-transformer for Voltage sag mitigation, the laboratory setup validates the PSCAD results obtained in chapter 4 with lower range approximately meets the higher range. Figure 5.1 shows the schematic of the test setup. The actual test setup is shown in fig 5.2. The test system is built for a voltage of single phase 230V, while IGBT and power diodes are of 600V. The experimental setup consists of an PWM switch of an IGBT and four power diodes connected in such a way that the switch acts as bidirectional switch, a two winding transformer of 1:1 ratio is connected as autotransformer, an two winding transformer with different tap settings at secondary side in order to create sag and swell of different percentages, a control circuit board to generate the PWM pulses according to sag developed by varying the phase shifter according to the value required for voltage sag/swell mitigation . The parameters of the prototype system are shown in table 5.1. The specifications of the Power devices are shown in table 5.2

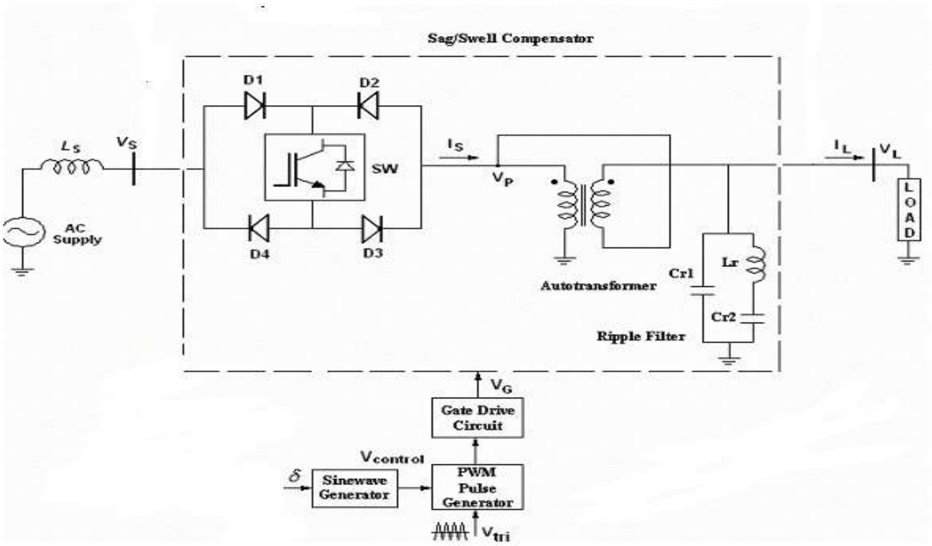


Fig 5.1 Schematic of test setup

Table 5.1 system parameters for the test setup

| | |
|---|---|
| Supply | 1-Phase, 230V, 50 Hz, A.C supply |
| PWM auto transformer<br>Tapping transformer | 230V/230V<br>230/(195V-265V) ± 15% |
| Ripple filter | L=1.26mH,C=0.22uF |
| Load | RC Load- R=1ohm,C=1uF |
| Switching frequency | 1500 HZ |

Table 5.2 Specifications of the power devices used in hardware setup

| Component | Rating |
|---|---|
| IGBT | 600V,70A |
| Diode | 600V,20A |
| Snubber capacitor | 40 $\mu$F,440V |
| Snubber resistor | 5 $\Omega$ |

## 5.2 Design of PWM Pulse generation Circuit

IGBT requires PWM Pulses to control turn ON and OFF and the design of PWM generation circuit is a very important aspect in this prototype setup. The fig 5.3 shows the control circuit for the generation of PWM Pulses. The control circuit is divided into four parts:

### 5.2.1 Lead and Lag Signal Generating Circuit

In this circuit a sine reference signal is generated by the step down transformer of 230/6V, 500ma. This reference signal is given to lead and lag circuit as shown in fig 5.3(a). LM324 Op-amp is used as lead and lag circuits. The outP.Ut of the lead circuit is an sine waveform which leads the reference signal by certain angle and the angle at which it leads can be varied by varying the resistance POT of 2K and 20K.similarly Lag circuit is also generates an sine waveform which lags the reference signal by certain angle, which is varied by varying the Pot's of 2K and 20K

### 5.2.2 Triangular wave generating circuit

The triangular generation circuit is as shown in fig 5.3 (b) generates the triangular signal by using IC XR 2206, which is a 16 pin IC, and the lowest frequency it can generate is 650Hz and the highest frequency is 1MHZ. This setup requires a switching frequency of 1.5KHZ, which can be generated by varying the 20k POT at pin 7. The triangular frequency is generated at pin 2.

### 5.2.3 PWM Pulse generating circuit

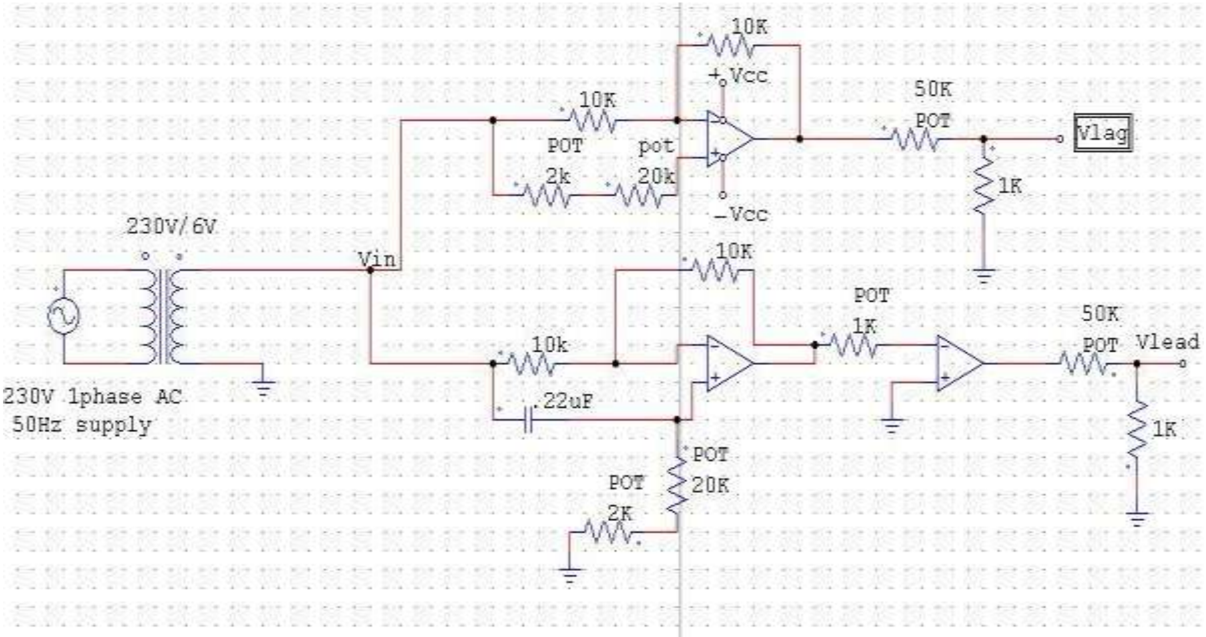
The lead or lag sine wave generated by LM324 and triangular wave generated by XR2206 is given to LM339 , which is used as a comparator and generates the PWM signals with switching frequency of 1.5KHZ as show in fig 5.3(c). If there is a swell condition, then leading signal is given to the inputof non- inverting terminal of the LM339, else if there is a sag condition, then lagging signal is given to the Non Inverting terminal of Op-amp. The angle of lead or lag signals depending on sag or swell condition are varied until the Load voltage reaches its nominal value

### 5.2.4 Gate Drive Circuit

The Pulses produced by the Pulse generator circuit cannot drive the IGBT because the Pulses are of low current; hence these Pulses are to be converted to high current Pulses, which are done by IR 2110 gate drive circuit as shown in fig 5.3(d). IR 2110 is a half bridge drive circuit, which can produce both positive and negative Pulses to drive a half bridge IGBT's at a time. The Pulses produced by the IR2110 are given to the gate terminal of IGBT through a series and parallel resistor of 1K and 10K to limit the current through gate.

This control circuit for PWM switched auto transformer mitigation of sag and swell is an **open loop method** i.e. sag/swell is created by changing the tap setting on secondary side of source side transformer and then leading or lagging angle is varied to vary the angle of PWM Pulses , which in turn vary the RMS voltage at load.

The fig 5.4 shows the PWM Pulse train for an angle of 20 ° lagging to the reference sine wave.



(a)

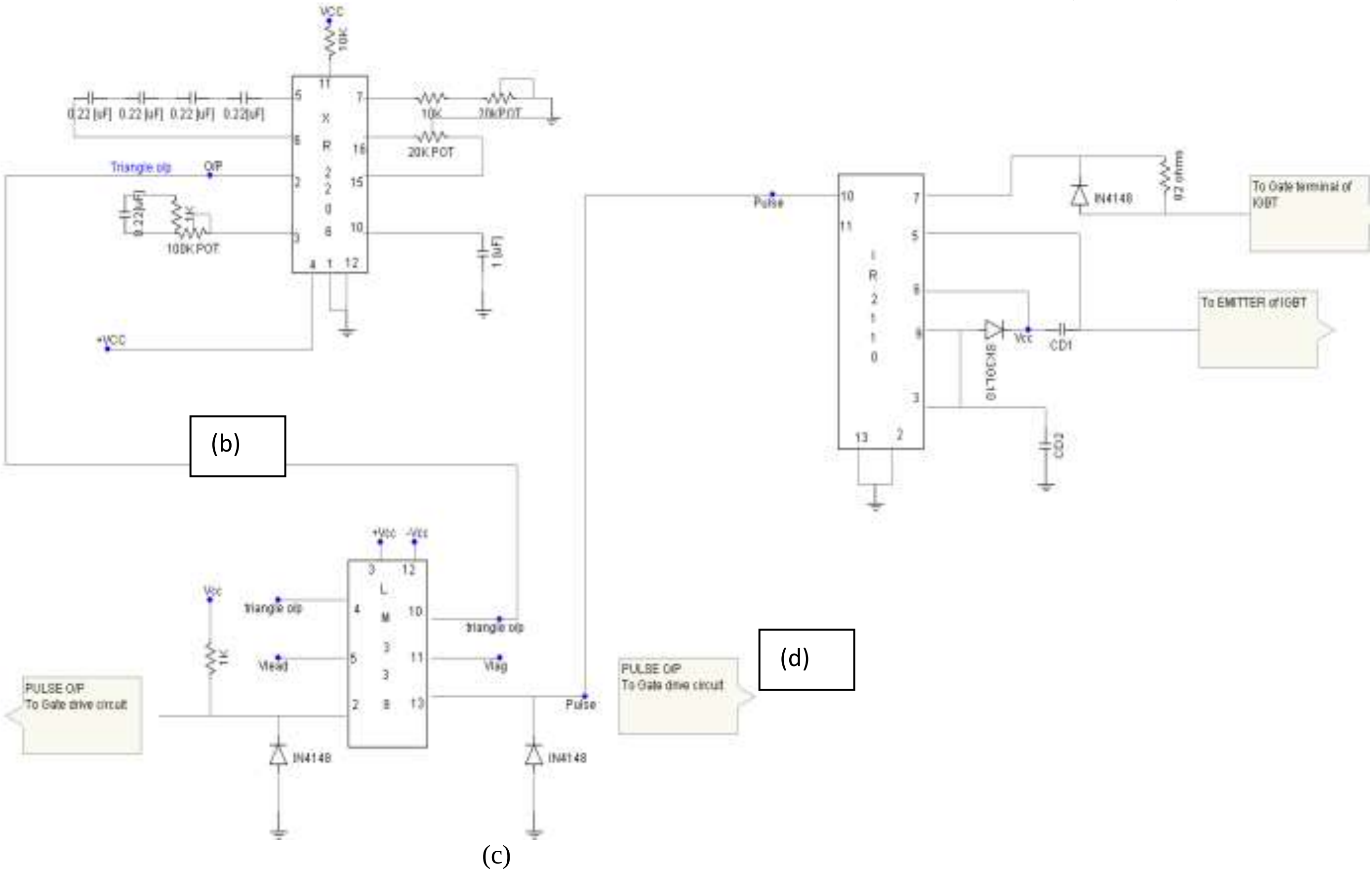


Fig 5.3 control circuit for PWM Pulses generation (a) Lead and Lag generation circuit (b) Triangular waveform circuit (c) PWM Pulse generation circuit (d) Gate drive circuit

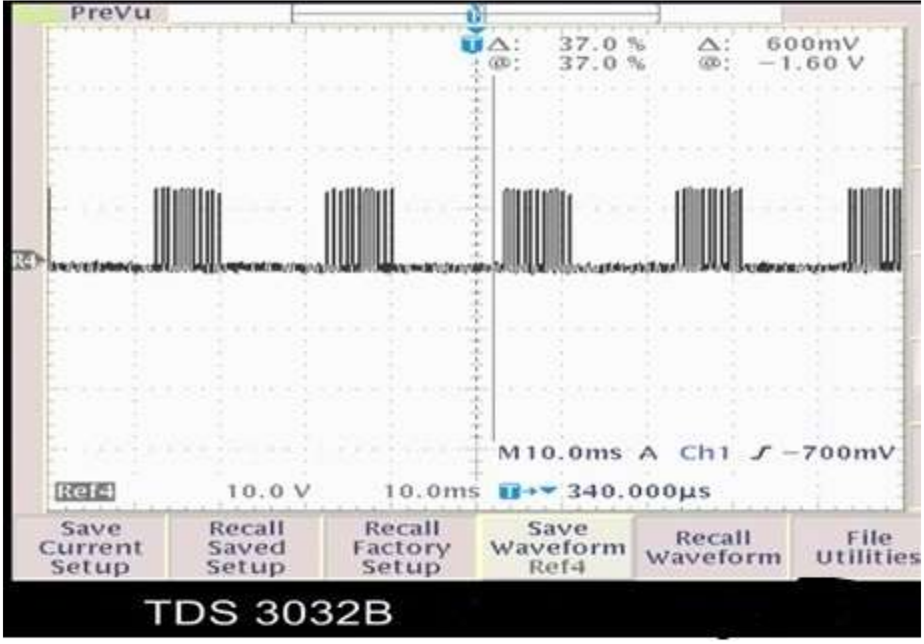


Fig 5.4 PWM Pulse train for an angle of 20 ° lagging to the reference sine wave

## 5.3 Design of Snubber circuit and ripple filter

### 5.3.1 Design of Snubber circuit

To determine the Snubber values, the system parameters should be known first and are shown in Table 5.1. The normal current of the system is 5 A RMS, and its maximum value is chosen as 10 A RMS. the peak of phase voltage is about 325 V. The Snubber should be designed such that the voltage across the IGBT (IRG4PC50F) should not increase above its breakdown voltage i.e. 600V

To determine the Snubber resistor and capacitor components, the value of the resistor is examined at first. The resistor has two roles. One is to dampen the energy transfer to the capacitor when the IGBT turns off, and the other is to limit the capacitor discharge current when the IGBT turns on. From the IGBT datasheet, it can be found that the maximum peak repetitive current is 120A. From the second role for limiting the initial discharging current of the capacitor, the resistor value is selected by from 600V/120A = 5$\Omega$.So that the resistor value is chosen to be 5$\Omega$.

The initial voltage drop across the Snubber resistance is given by 230 $\times \sqrt{2} \times 5$=282.84

The initial voltage drop which is similar to a 90% of nominal voltage where it is considered that *Vin*has a 10% voltage sag. In the above calculation, the worst case is assumed that the peak value of the maximum load current of 120 A (120$\times$2), and as the current of inputside in the autotransformer is twice the load current, the peak load current is multiplied by two in the equation.

The highest Snubber voltage occurs at the condition of the minimum on time, in other words maximum turn-off time. When the input voltage has minimum voltage sag, which generates this condition in this system, the minimum allowable voltage is 0.9 P.U (per unit) so that the voltage having 90% voltage sags is chosen as the worst case. The minimum turn-on time is determined from eq (1), which gives a 75% duty-cycle.

$$V_{out} = D.V_{on} + (1-D).V_{off}$$

$$=D.2V_{in} - (1-D)2V_{in}.1/2 =2$$

$$V_{in}(3/2D-1/2) \quad (1)$$

In cases where the 1.5 kHz switching frequency and D = 75%, the IGBT is in the on-state for 500 $\mu$s and in the off-state for approximately 170 $\mu$s. The approximate capacitance value of the Snubber is determined by two conditions. The first condition is that the peak voltage during the IGBT off-state should be lower than 5000 V, and the second condition is that the capacitor voltage needs to discharge lower than 10% of its charged value during the IGBT turn-on. When the minimum IGBT on-state time is greater than 2.5 ×RC, which means 500 ×s > 2.5 × RC $\rightarrow$C < 45$\mu$ F, the second condition is satisfied, which results in a 40$\mu$F capacitor Snubber capacitor. The Snubber values for the IGBT are R=5$\Omega$ and C=40$\mu$F.

### 5.3.2 Design of ripple filter

Ripple filer is connected at the load to remove the higher order harmonics. The design of the ripple filter for this prototype is mentioned in section 5.2.1. The Values of ripple filter are $C_{f}$ =0.22$\mu F$, $L_f$ = 1.26mH. The Inductor filter value is not readily available in market and it is designed by using **Ferrite core** and **copper wire**. The copper wire is wound on a ferrite core and the inductor value is measured using **LCR meter**.

## 5.4 Experimental Results

**Test case I**: Mitigation of voltage sag using PWM switched transformer Prototype.

- The prototype is built for 230V, but it is tested for 20 V only due to some operating difficulties.
  - Vs = 15.4 before voltage sag
  - Vs = 13.4 at 13% sag
  - $V_p$=7.7 V at primary of PWM transformer
  - $V_{Load}$=15.4 at secondary of PWM transformer
  - The waveforms for the above case as shown
- $V_{Load}$ with capacitive only capacitive filter is shown in fig 5.5

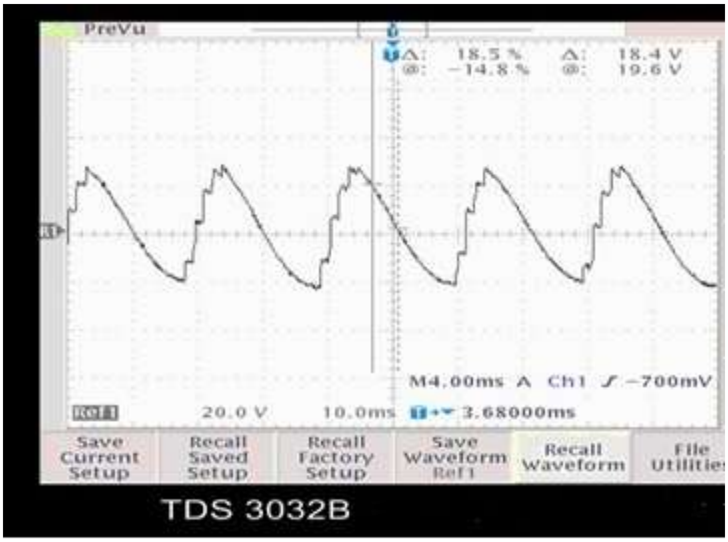


Fig 5.5 load voltage with capacitor only filter

- Wave forms for Vref, V sag, V load with ripple filter is shown if fig 5.6

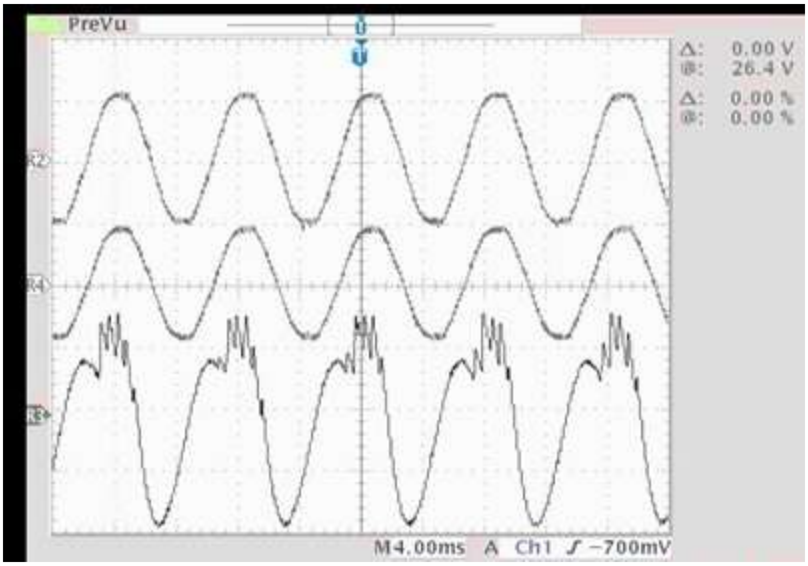


Fig 5.6 waveforms for a Voltage sag of 13% with ripple filter

## 6. Main Conclusion and Scope Of Future Work

### 6.1 Conclusion

In this project simulation of various custom power devices i.e. DVR, DSTATCOM, PWM SWITCHED AUTO TRANSFORMER for mitigation of voltage sags and swells are modelled and simulated in PSCAD/EMTDC is implemented for low voltages.

An industrial system test system with Induction motor and sensitive loads are simulated in PSACD/EMTDC and it shows that due to the presence of induction Motors in the system , the voltage at the sensitive load cannot reach its rated value instaneously after the fault is cleared. Starting of Induction motors causes voltage at the sensitive loads connected system, it can be eliminated by starting the induction the Induction motor with starters. Faults are the main causes of the voltage sags. Custom power devices DVR, DSTATCOM which uses inverter topology are simulated for different sag and swell conditions and it has shown that DVR can mitigate up to 50% of sag for DC voltage($V_{DC}$ =5KV, 60% of sag for $V_{DC}$ =7KV , 70% of sag for $V_{DC}$ =10KV. A 12 pulse DVR generates fewer harmonic than a 6 pulse DVR and at the 12 pulse DVR can mitigate sags due to unbalanced faults. DSTATCOM can mitigate voltage sags up to 80% due to three phase faults with $V_{DC}$ =50KV and voltage sags up to 30% due to Sudden load switching with $V_{DC}$ =19KV. It is shown that for the same voltage sag compensation DVR requires less energy than DTATCOM.

A new Voltage sag mitigation topology called PWM switched auto transformer is modelled and simulated with peak and RMS voltage as a reference. This topology requires only one PWM switch per phase as compared to DVR or DSTATCOM requires two switches per phase. The PWM switched auto transformer does not require energy storage device for mitigation of voltage sag as compared to DVR and DSTATCOM requires energy storage elements. Hence it is shown that this device can mitigate up to 80% sag and for the same voltage sag/swell compensation PWM switched autotransformer is the most economical device for voltage sag mitigation with good performance.

## 6.2 Scope of Future Work

- Hardware Implementation of PWM Switched Auto Transformer for closed loop control for voltage sag/swell mitigation has to be done.

PMW Switched Auto Transformer for mitigation of voltage sag due to unbalanced faults has to be done

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|  | **Kalappagari Nagendra** hasreceived the B.Tech degree in Electrical Engineering from Kuppam Engineering College Kuppam Affiliated to Jawaharlal Nehru Technological University-Anantapur (JNTUA), India now currently PG scholar, pursuing M.Tech, area of specialization is Power Electronics in Kuppam Engineering College, Jawaharlal Technological University Anantapur, Andhra Pradesh, India. |
|  | **Y. Damodharam**has obtained his B.Tech in EEE from Kuppam Engineering College, affiliated to JNTUH in the year 2006. He has obtained M.Tech in power system emphasis on High Voltage Engineering from JNTU Kakinada in the year 2010. He has 7 years of Teaching experience. Currently working as Associate Professor in Kuppam Engineering College in the Department of EEE. His area of research is renewable energy sources, High Voltage engineering & power systems |
|  | **Vusirika Prasad Reddy**has received the B.Tech. degree from Jawaharlal Nehru Technological UniversityBachelor of Technology (B Tech), Electrical and Electronics Engineering (2003 – 2006) ,Hyderabad, India, in 2000, the M.Tech Electrical and Power Transmission Installers in electrical engineering from National Institute of Technology Warangal (2006 – 2008 ), India, in 2008, and the Ph.D. degree in electrical. From December 2007 to till date. He is currently Associate with Bharat Heavy Electricals Limited as Senior Engineer |
|  | **VelappagariSekhar**has obtained his B.Tech in EEE from Kuppam Engineering College, affiliated to JNTUH . He has obtained M.Tech in power system emphasis on High Voltage Engineering from JNTU Kakinada. He has 7 years of Teaching experience. Currently working as Associate Professor in Kuppam Engineering College in the Department of EEE. His area of research is renewable energy sources, High Voltage engineering & power systems |
|  | **A. Arul Prakash has** obtained his doctoral degree from Anna university Chennai. M.E. degree from Salem, 2006 and B.E. Degree both from BharatiyaUniversity Coimbathre,2002. He has 9 years of teaching experience. His research area isPower Electronics, and Renewable Energy Sources &SCT.. Currently working as an HOD of EEE Department & Director, R & D in Kuppam Engineering College, Kuppam, and Chittoor Dist. Andhra Pradesh. He received UGC RESEARCH GRANT during P.hd programme. |