ANALYSIS OF TOTAL HARMONICS DISTORTION IN DVR COMPENSATED SYSTEM

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***Abstract* – Voltage sags are the major source of power quality related problems. Dynamic Voltage restorers (DVR) are used to protect sensitive loads from the effects of voltage sag on the distribution feeder. It injects voltage in series with the system voltage to compensate the sag. This paper presents a power system operation with PI controller approach. Total Harmonics Distortion (THD) is calculated for the system without and with compensation. It is also evaluated when DVR is in operation. The results obtained for both cases are compared. The impact of DVR operation on THD is analyzed using MATLAB software.**

Keywords: DVR, Power Quality, THD, Voltage Sag.

I.INTRODUCTION

One of the most important power quality issues is voltage sag because the increasing usage of voltage sensitivity devices has made industrials processes more susceptible to supply voltage sags [1]. Voltage sag is not a complete interruption of power; it is a temporary drop below 90 percent of the nominal voltage level. Most voltage sags do not go below 50 percent of the nominal voltage, and they normally last from 3 to 10 cycles—or 50 to 170 milliseconds. Voltage sags are caused by abrupt increases in loads such as short circuits or faults, motors starting, or electric heaters turning on, or they are caused by abrupt increases in source impedance, typically caused by a loose connection [2]. Voltage sag mitigation devices are classified into three categories; (i) Traditional Solutions: Voltage Control included Transformer and Tap Changers. Both are mechanical and SCR switched units. In this technology; servo-variac technology and ferro-resonant transformers are used as a voltage sag mitigation devices [3]. These devices are heavy, bulky and inefficient so they are rarely used [4]. (ii) Uninterruptible Power Supplies (UPS): The main disadvantage with the UPS is that it uses batteries as its DC storage system making it more expensive to use than the DVR which uses a bank of capacitors [5]. (iii) Dynamic Voltage Restorer (DVR): The voltage source converter (VSC) connected in series with the grid as a static series compensator (SSC) is also known as commercial as the Dynamic Voltage Restorer (DVR). It is used to protect for any voltage sags caused by different faults and condition. It is a power electronics device. The basic operation principle of the DVR is to inject an appropriate voltage in series with the supply through injection transformer whenever voltage sag or voltage swell is detected [6]. The DVR using pulse width modulation technology has controlled Phase and amplitude [7]. The efficiency of the DVR depends on the performance of the efficiency control technique involved in switching the inverters [8].

The basic structure of a DVR is shown in Fig.1; Section I briefly describes the sag and its mitigation devices. Section II discusses the DVR basic structure component section. DVR compensation technique is explained in section III, section IV shows the electrical circuit model of DVR, section V discusses the PI controller strategy employed for inverter switching in the DVR [9, 13]. The simulation model is developed using the simulink and utility of MATLAB in section VI and section VII described the THD.

II. DVR STRACTURE

A basic structure for a DVR shown in Fig.1.

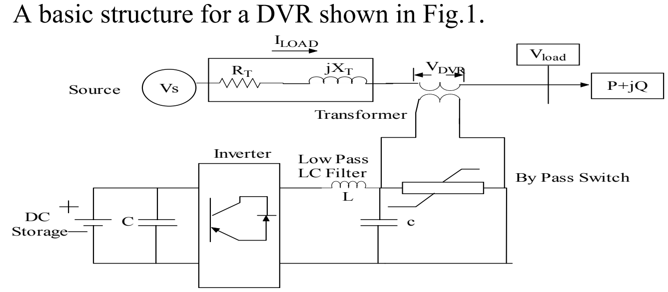

Fig.1. Basic Structure of Dynamic Voltage Restorer

The device consists of five main sections; (i) Energy Storage Unit: It is energy storage in DC form Flywheels, Lead acid batteries, Superconducting Magnetic Energy Storage (SMES) and super-capacitors can be used as energy storage devices, below are estimates of the typical energy efficiency of four energy storage technologies: batteries – 75 %, Fly wheel – 80 %, Compressed air – 80%, SMES – 90% [9]. (ii) Energy conversion for charging (converter): Inverter system to convert from dc storage to ac [10]. (iii) Passive Filters: Filters are used to convert the PWM inverted pulse waveform into a sinusoidal waveform. This is achieved by removing the unnecessary higher order harmonic components generated from the DC to AC conversion in the VSI, it is clear that higher order harmonic components distort the compensated output voltage [11]. (iv) By-Pass Switch: It is used to protect the inverter from high currents. So that a by-pass switch (crowbar circuit) is incorporated to by-pass the inverter circuit. (v) Voltage Injection Transformers: For a DVR in three-phase system, Three Single-phase transfer units or one three Phase transformer unit can be used [11].

III. DVR COMPENSATION TECHNIQUES

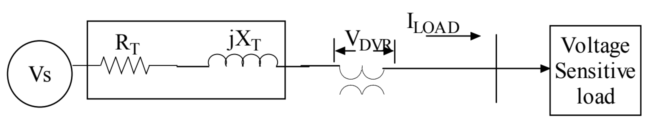

Fig.2. Power System with DVR

Power System with DVR is shown in Fig.2.
Following two compensation techniques are used [14].
(i) Pre-Sag Compensation: In this technique the DVR supplies the difference in voltage (V_{DVR}) between the pre-sag ($V_{pre\text{-}sag}$) and the sag voltage (V_{sag}), thus restore the voltage magnitude and the phase angle to that of the pre-sag value as shown in Fig.3. This technique is used for nonlinear load.

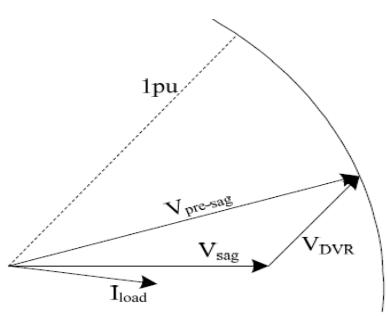

Fig.3. Pre-Sag Compensation Technique

(ii) In-Phase Compensation: The compensated voltage is in-phase with the sagged voltage and it compensate for the voltage magnitude only. Therefore the advantage of this technique minimizes the voltage injected by the DVR. It is recommended for the linear loads [12]. In this method pre-sag ($V_{pre\text{-}sag}$) is the sum of the DVR supplies voltage (V_{DVR}) plus the sag voltage (V_{sag}) as shown in Fig.4 .

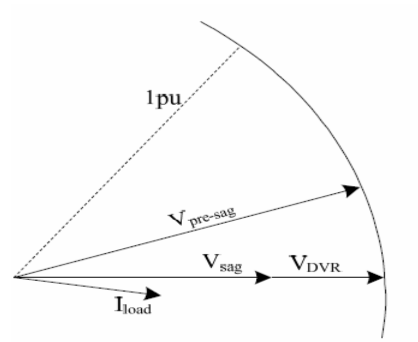

Fig.4. In-Phase Compensation Technique

IV. SERIES VOLTAGE CONTROLLER

The electrical circuit model to indicate voltage injection by a DVR system is shown in Fig.5.

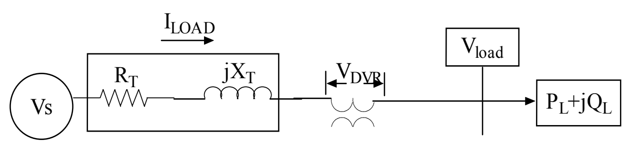

Fig.5. Electrical Circuit Model for DVR Voltage Injection

The series injected voltage of DVR can be written can be as [13].

$$V_{DVR} + V_{sf} = V_{Load} + Z_T I_{Load} \quad (1)$$

Or $$V_{DVR} = V_{Load} + Z_T I_{Load} - V_{sf} \quad (2)$$

Where

$Z_T = R_T + jX_T$

V_{DVR} is voltage supply by the DVR,

V_{Load} is the desired load voltage magnitude,

Z_T is the load impedance,

I_{Load} is the load current,

V_{sf} is the system voltage during fault condition,

Current is the load side can be calculated as

$$V_{load} \; I_{Load} = P_L + j\,Q_L \quad (3)$$

$$I_{Load} = \left(\frac{P_L + j * Q_L}{V_{Load}} \right) \quad (4)$$

Where load voltage consider as a reference, P_L is load active power, and Q_L is load reactive power.

Then DVR voltage can be written as

$$V_{DVR}\angle\alpha = V_L\angle 0^o + Z_T I_{Load}\angle(\beta-\theta) - V_{sf}\angle\delta \quad (5)$$

Where α, β and δ are the angles of V_{DVR}, Z_T, and V_{sf} respectively

$$\theta = \tan^{-1}(\frac{Q_L}{P_L})$$

Where θ is load power factor angle.

The apparent power injection by the DVR is given by

$$S = V_{DVR} * I_L \quad (6)$$

V. CONTROL TECHNIQUES FOR DVR

Voltage sag is created at load terminals by a three-phase fault as shown in Fig.6. Load voltage is sensed and passed through a sequence analyzer.

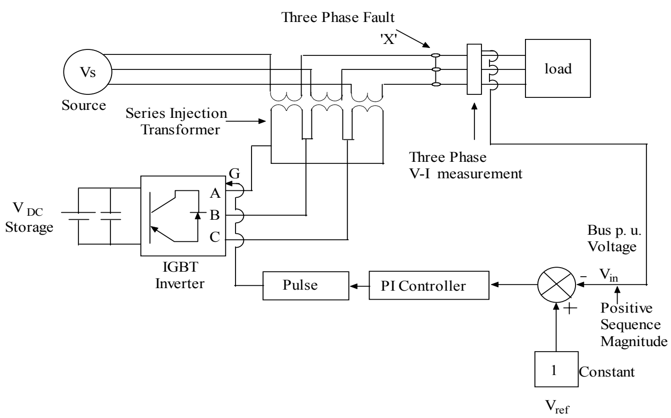

Fig. 6. Circuit Model of DVR Test System for Voltage Sag

The magnitude is compared with reference voltage (V_{ref}). Pulse width modulated (PWM) control technique is applied for inverter switching so as to produce a three phase 50 Hz sinusoidal voltage at the load terminals. Chopping frequency is in the range of a few KHz. The IGBT inverter is controlled with PI controller in order to maintain 1 p.u. voltage at the load terminals i.e. considered as base voltage =1p.u.

A proportional-integral (PI) controller (as shown in Fig.7) drives the plant to be controlled with a weighted sum of the error (difference between the actual sensed output and desired set-point) and the integral of that value. An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the V_{ref} and V_{in}. Output of the controller block is of the form of an angle δ, which introduces additional phase-lag/lead in the three-phase voltages. The output of error detector is

$$V_{ref} - V_{in}. \quad (7)$$

V_{ref} equal to 1 p.u. voltage

V_{in} voltage in p.u. at the load terminals.

The controller output when compared at PWM signal generator results in the desired firing sequence.

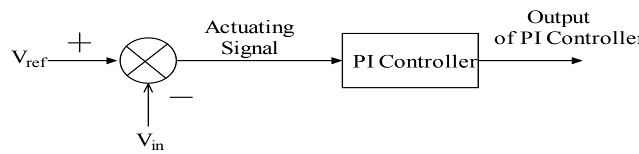

Fig.7. Schematic of a Typical PI Controller

The modulated angle is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 120° and 240°. In this PI controller only voltage magnitude is taken as a feedback parameter in the control scheme [13].

The sinusoidal signal $V_{control}$ is phase-modulated by means of the angle δ and the modulated three-phase voltages are given by

$$V_a = \sin(\omega t + \delta) \quad (8)$$

$$V_b = \sin(\omega t + \delta + 2\pi/3) \quad (9)$$

$$V_c = \sin(\omega t + \delta + 4\pi/3) \quad (10)$$

Table1. PWM Generator System Parameter

Parameters	Value
Generator Mode	3-Arm Bridge, 6 Pulses
Carrier Frequency(Hz) (F_c)	1080
Sample Time	5×10^{-6}
Frequency Modulation Index , $m_f = f_c/f_1$	$m_f = 1080/50$

Where f_1 is the fundamental frequency.

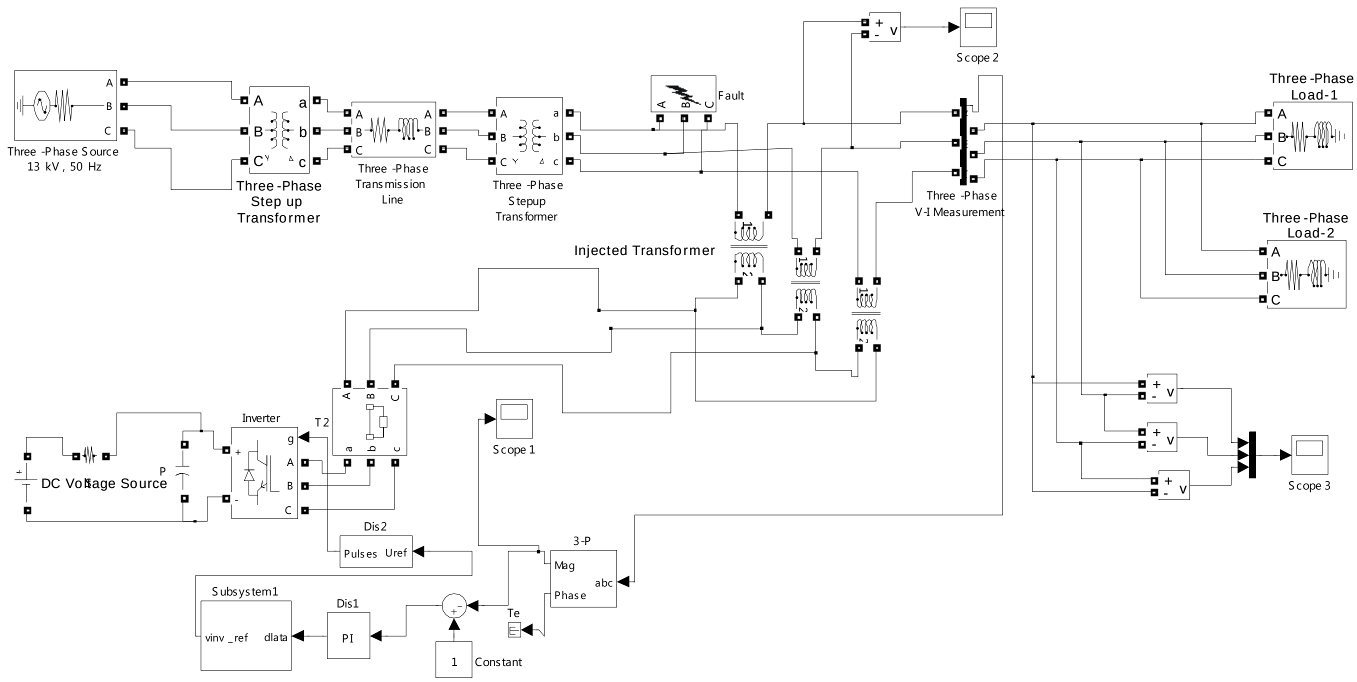

Fig.8. MATLAB Simulink Model of DVR Test System for Voltage Sag

The modulating angle is applied to the PWM generators in phase R. The angles for phases Y and B are shifted by 120^o and 240^o respectively.

VI. MATLAB SIMULINK TEST SYSTEM FOR DVR TEST SYSTEM

Circuit Model of DVR Test System for Voltage Sag as shown in above Fig.6. V_s is the incoming supply voltage which is connected to load. Series voltage compensation technique is used for compensation. It consists of an injection transformer, the secondary winding of transformer, which is connected in series with the transmission line. a PWM (pulse-width modulated) voltage source inverter connected to the injected transformer and dc energy storage connected to inverter bridge. Firing angle of inverter is controlled by PI controller [13]. Input of PI controller which is the actuating signal .which is obtained by comparison of the bus p.u. voltage with standard p.u. voltage.

MATLAB Simulink diagram of the test system for DVR is shown in Fig.8. This is composed of 13 kV, 50 Hz generator, feeding transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/11 kV.

Case I: Simulation Result of Voltage Interruption during Three-Phase Fault without DVR

A fault is applied at point x via a resistance of 0.66 Ω which results in a voltage sag of 16.75%. Fault is applied for transition time from 0.4 to 0.6 sec as shown in Fig.8. The simulation result with out using DVR energy storage system is shown in Fig.9 and p.u basis in Fig.10.

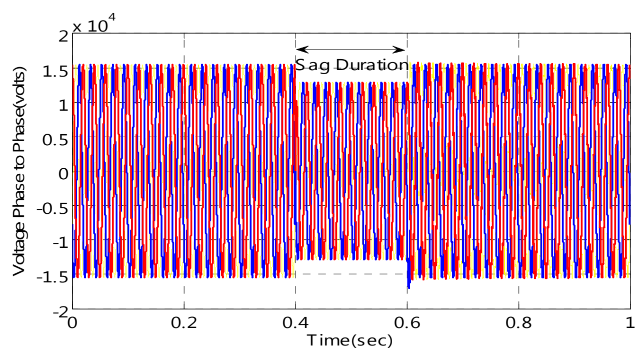

Fig.9. Three Phase, Phase to Phase Voltage with out DVR Energy Storage of 5kV.

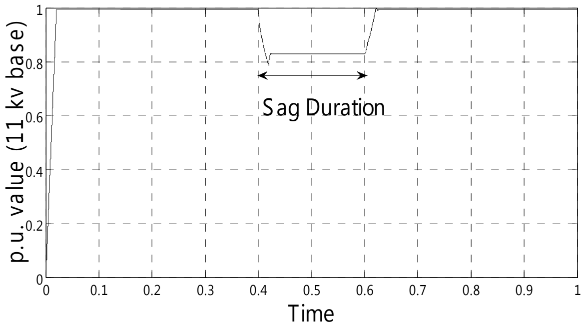

Fig.10. Voltage p.u. at the load point: without DVR Energy Storage of 5 kV

Case II: Simulation Result of Voltage Interruption During Three-Phase Fault Using DVR:

In this case DVR energy storage of 5 kV is used along with the system used in first case. Simulation is shown in Fig 11, result shows of compensated voltage and on p.u. basis in Fig.12.

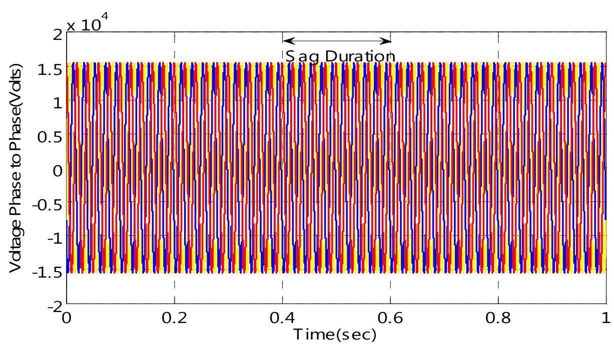

Fig.11.Three Phase, Phase to Phase Voltage with DVR Energy Storage of 5 kV

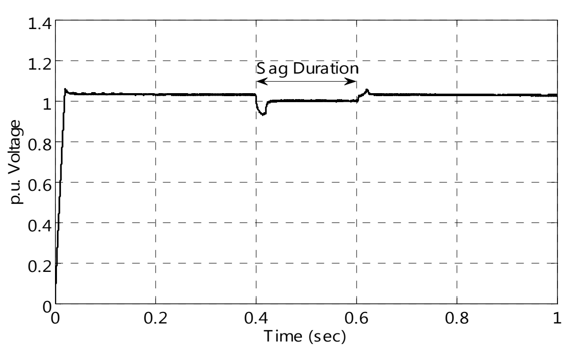

Fig.12. Voltage p.u at the load point: with DVR Energy Storage of 5kV.

Comparator output provides the actuating signal which is the difference between the reference voltage V_{ref} and input voltage V_{in} as shown Fig.13. Actuating signal feed which is the input for the PI controller and output of PI controller as shown Fig.14.

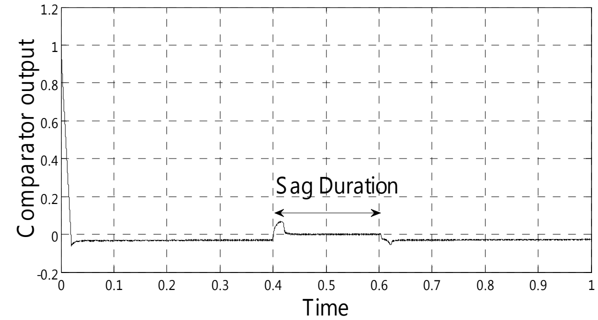

Fig.13.Comparator Output

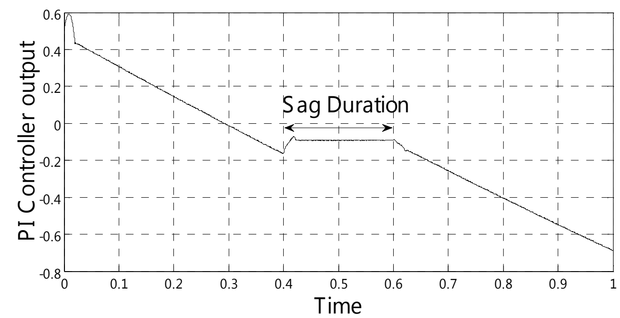

Fig.14. PI Controller Output

VII. TOTAL HARMONICS DISTORTION (THD) ANALYSIS

Harmonic distortion is caused by the high use of non-linear load equipment such as computer power supplies, electronic ballasts, compact fluorescent lamps and variable speed drives etc, which create high current flow with harmonic frequency components. The limiting rating for most electrical circuit elements is determined by the amount of heat that can be dissipated to avoid overheating of bus bars, circuit breakers, neutral conductors, transformer windings or generator alternators. THD is defined as the RMS value of the waveform remaining when the fundamental is removed. A perfect sine-wave is 100%; the fundamental is the system frequency of 50. Harmonic distortion is caused by the introduction of waveforms at frequencies in multiples of the fundamental i.e. 5^{th} harmonic is 5x the fundamental frequency 250 Hz. Total harmonic distortion is a measurement of the sum value of the waveform that is distorted. SCR type inverter is produces high levels of harmonics [15]. THD is measured in terms of the harmonic constant of the wave, as given by equation (11).

$$THD = \frac{\left[\sum \left(\text{Amplitudes of All Harmonics}\right)^2\right]^{\frac{1}{2}}}{\text{Amplitude of Fundamental Harmonic}} \tag{11}$$

A measure of distortion represented by a particular harmonics is simply the ratio of amplitude of harmonics to that of fundamental harmonics distortion (HD) is then represented by,

$$D_2 = \frac{E_2}{E_1}, D_3 = \frac{E_3}{E_1}, \; D_4 = \frac{E_4}{E_1} \qquad (12)$$

Where D_N represented distortion of n^{th} harmonics and E_N represented harmonics of n^{th} harmonics, where (N=1, 2, 3, 4…………)

$$THD = \sqrt{(D_2^2 + D_3^2 + D_4^2 + ...)} = \frac{\sqrt{(E_2^2 + E_3^2 + E_4^2 + ...)}}{E_1} \qquad (13)$$

Percentage Harmonics Distortion=

$$THD = [\sqrt{(D_2^2 + D_3^2 + D_4^2 + ...)}] * 100$$
$$THD = [\frac{\sqrt{(E_2^2 + E_3^2 + E_4^2 + ...)}}{E_1}] * 100 \qquad (14)$$

Simulation result shows that when system simulation is carried on without DVR with voltage sag 19% then THD is 0.00% as shown Fig.15,

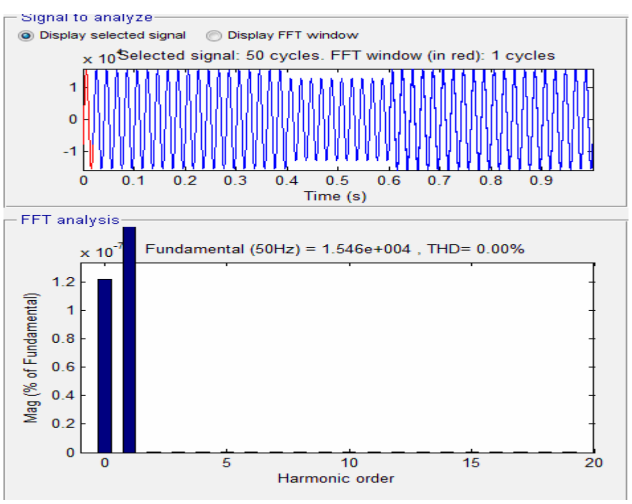

Fig.15. THD in Harmonics Order

When DVR with energy storage capacity 5kV, MATLAB simulation is carried out with PI controller then total harmonic distortion is calculated 26.20% as shown Fig.16.

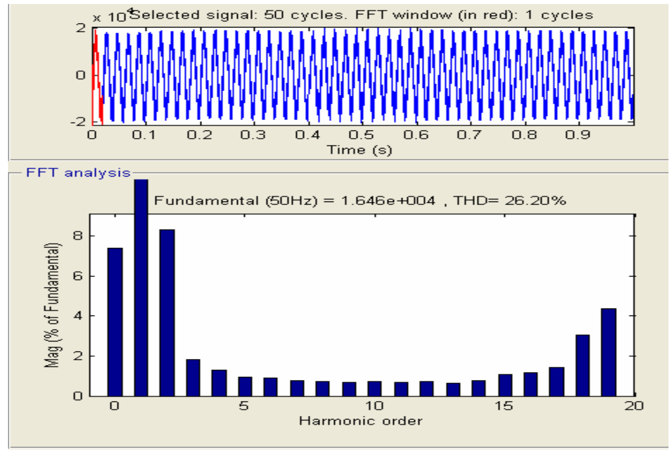

Fig.16. THD in Harmonics Order

Similarly, when simulation results are obtained with different voltage sag condition is shown in below Table 2.

Table2. Comparison Table between Different Voltage Sag Versus THD

DVR Operation	Voltage Sag	THD
NO	19%	0%
YES	25%	26.20%
YES	27%	26.20%
YES	32%	26.20%
YES	34%	26.20%
YES	36%	26.20%

Table 2 shows comparison between the THD with different voltage sag conditions. It shows that when DVR is not in operation then THD is 0%.When DVR in operation with different voltage sag condition. Then results shows that THD maintains a constant value during the different voltage sag condition.

VIII. CONCLUSION

This paper presents the performance analysis of a series type compensator involving a PI controller. The employed scheme is able to compensate voltage sag even for the long term faults. Presence of DVR introduces excessive harmonics in the system which further needs suitable filtering to bring down the THD within permissible limits. Results obtained via MATLAB simulation which shows the increased levels of THD during DVR operation. The DVR compensation technique may be further improved to form a combined passive power filter and dynamic voltage regulator.

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