AMSE JOURNALS-AMSE IIETA publication-2017-Series: Modelling C; Vol. 78; N°3; pp 274-288
Submitted July 31, 2017; Revised Jan. 04, 2018; Accepted Jan. 03, 2018

Improvement of Power Quality in Underground Coal Mines Using Controllers

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Abstract

Power quality is an important problem which has to be considered carefully in mining industry. Underground coal mining industry uses different machinery such as shearers, crushers, continuous miners, Armoured Face Conveyor (AFC) etc. which are sensitive to voltage fluctuations. Machines used are induction motors which are rated high because high torque is required for cutting of coal. These motors are sensitive to voltage fluctuations as torque is proportional to square of the voltage. Generally, mining industries are located in remote areas and in underground mines, transformers are not allowed inside the mines for safety purposes and hence cables are used in underground mines for transmission of power. The value of voltages goes on reducing with increasing depth of the mines, and it becomes critical. Voltage sag is one of the common and serious issue to the mining industry. In order to maintain constant voltage, there should be some compensating devices to compensate voltage sag. In order to solve voltage sag problem, one of the underground mine is considered for case studies. This paper focused on improvement of power quality by using Distribution Static Compensator (DSTATCOM), with three controllers such as Proportional Integral (PI) controller, Hysteresis Voltage Controller and Fuzzy Logic Controller. These controllers are implemented in MATLAB/SIMULINK software and a comparative analysis is presented based on the Total Harmonic Distortion (THD) with and without controllers.

Key words

Power quality, Underground coal mines, Distribution static compensator (DSTATCOM), Proportional integral (PI) controller, Hysteresis voltage controller, Fuzzy logic controller and total harmonic distortion (THD).

1. Introduction

India’s electricity sector consumes about 72% of the coal produced in the country. Longwall coal mining is an efficient mining method that can extract a high percentage of coal from a seam. In a Longwall coal mine, two long, horizontal and permanent tunnels known as gate-roads are cut into a coal seam to form the boundaries for a large rectangular block of coal, known as a Longwall panel [1]. Each gate-road is typically 5–6-m wide. A typical longwall panel is 200–400 m wide, and 2–5 km long, which is the length of the gate-roads. Figure 1 shows the perspective view of longwall mining system where major pieces of mining equipment are installed across the longwall face. Longwall mining is a method for extracting coal from underground mines. The mining technology involves a longwall shearer, which is a 15 m long, 100 tones machine that has picks attached to two drums, which rotates at 30–40 rev/min. A longwall face is the mined area from which material is extracted. The shearer removes coal by traversing a face at approximately 25 min intervals [2].

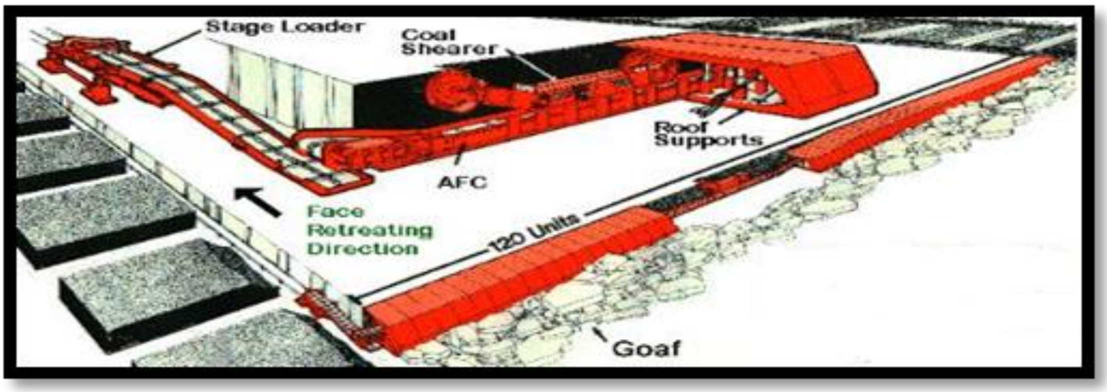


Figure 1. Perspective and closeup view of longwall mining system

The three main items of longwall mining equipment installed on the face are the shearer, which cuts the coal, the armored face conveyor, which guides and locates the shearer and transports the coal to a conveyor system in the gate-road and the roof support system. The armored face conveyer has twin steel chains, which are sprocket driven by 800–1500 kW motors situated in the gate-roads [3]. Figure 2 shows shearer cutting in a Mine –A.

Figure 2. Shearer cutting at Longwall face (Mine -A)

Therefore, the equipments used in underground coal mine are induction machines which are rated high because high torque is required for cutting of coal. Power consumption in a longwall face is the highest in underground mines. These motors are sensitive to voltage fluctuations as torque is proportional to square of the voltage. Generally mining industries are located in remote areas and in underground mines transformers are not allowed inside the mines for safety purposes as per Indian Electricity Rules Act 1956, and hence cables are used in underground mines for transmission of power [4]. As we go deeper in mines the level of voltage goes on decreasing. Therefore, there will be voltage sag on the machines, so that voltage fluctuations increases on the machines which indirectly affects the torque of the machine. Voltage sag causes machines to trip which in turn results in lengthy delays which causes production and revenue loss to the mining industry. Voltage sag is an important power quality problem. The main target in designing and operating a mine is to safeguard for the electrical machines and workers, with an increasing tendency in increasing the power quality. In order to maintain constant voltage, there should be some compensating devices to compensate voltage sag.

There are many compensating devices in the literature among them is Custom Power Devices (CPD). In this paper DSTATCOM is used as one of the CPD for improving power quality. The viability of DSTATCOM based on the utilization of control algorithms for producing switching signals for the voltage source converter [5]. In order to control DSTATCOM, many controllers are reported in the literature many CPD'S are proposed and developed to nullify various PQ issues in a distribution system. These CPD'S are categorized as DSTATCOM, Dynamic Voltage Restorer (DVR) and Unified Power Flow Conditioner (UPFC) which are used for this purpose. The success of DSTATCOM depends upon the use of controllers for generating the switching signals for VSC. For the control of DSTATCOM, various control algorithms are reported in the literature. Gothelf Natan et al. referred the hoisting machine in mining industry changing the load rapidly, which further influences the PQ of the electrical system [6]. Grunbaum et al. illustrated about Flexible AC Transmission Systems (FACTS) devices to enhance quality of supply to mining industry [7]. Parag Nijhawan et al. implemented PI Controller to decrease harmonic distortion on the distribution network when induction furnace is load as in steel industry [8]. Bhim Singh et al. presented PI Controller to improve the response and to reduce the overshoot of the unbalanced load [9,10].

Three controllers are proposed and they are PI controller, Hysteresis Voltage controller and Fuzzy logic controller. These controllers are implemented in MATLAB/SIMULINK software and there THD'S are compared.

2. Control of DSTATCOM

Distribution Static Compensator (DSTATCOM) is a voltage source inverter based static compensator (similar in various respects to the DVR) that is utilized for rectification of voltage dips. The DSTATCOM is adequate in getting endlessly inductive or capacitive compensation to its maximum value. The DSTATCOM checks the line waveform with a reference signal, and consequently, it can give the right measure of lagging or leading reactive compensation to diminish the voltage variations. The significant parts of a DSTATCOM are a DC capacitor, inverter module, an AC filter and PWM control strategy [11]. Figure 3 gives the schematics of a control framework utilizing DSTATCOM. DSTATCOM is regulated by means of Pulse Width Modulation (PWM) generator. Output of the model is processed with an error detector and it is fed to a fuzzy logic controller. The output angle 'δ' of controller is phase modulated depending on the controller actions. These signals are provided to PWM generator and the output of the PWM generator will compensate the voltage sag and improves the performance of DSTATCOM [9].

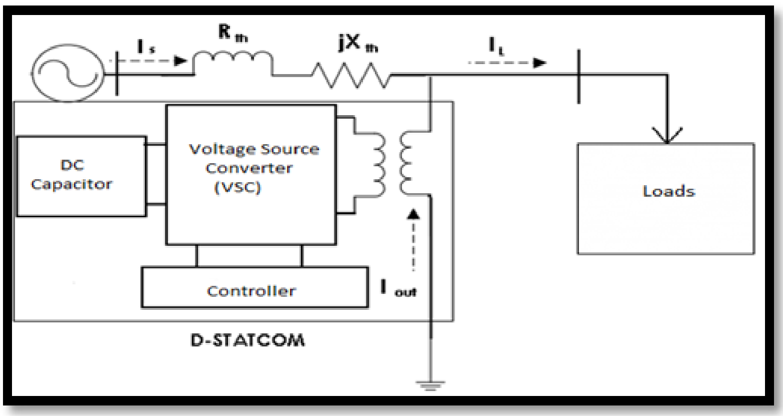


Figure 3. Control scheme of DSTATCOM

3. Controllers

3.1 PI controllers

The main aim of PI controller scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. The control system only measures the RMS voltage at the load point, i.e., no reactive power measurements are required [11]. 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 favored in Flexible Alternating Current Transmission System (FACTS) applications. High switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses. The controller input is an error signal obtained from the reference voltage and the RMS value of the terminal voltage measured. Such error is processed by a PI controller the output is the angle 'δ', which is provided to the PWM signal generator. It is important to note that, in this case, indirectly controlled converter, there is active and reactive power exchange with the network simultaneously: 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 to drive the error to zero, i.e., the load RMS voltage is brought back to the reference voltage. Figure 4 shows the scheme of PI controller.

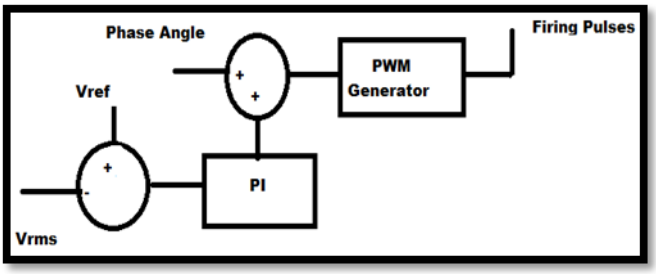


Figure 4. Block diagram of PI controller

$$V_A = \sin(wt + \delta) \quad (1)$$

$$V_B = \sin(wt + \delta - 120°) \quad (2)$$

$$V_C = \sin(wt + \delta + 120°) \quad (3)$$

Output of comparator = V_{ref} -V_{rms} (4)

where V_{ref} is per unit reference voltage V_{rms} is voltage in per unit at the load terminals

PI controller input is an actuating signal which is the difference between the V_{ref} and V_{rms} Output of the controller block the angles. The angle provides to PWM signal generator to obtain desired firing sequence.

Hysteresis voltage controller

Hysteresis Voltage Controller is utilized to control load voltage and decide exchanging signals for inverter switches. The control technique applied in this paper is based on voltage error. It consists of a comparison between the output voltage V_o and the tolerance limits (V_H, V_L) around the reference voltage $V_{ref.}$ While the output voltage V_o is between upper limit V_H and lower limit V_L, no switching occurs and when the output voltage crosses to pass the upper limit (lower band) the output voltage is decreased (increased) which is shown in Figure 5. The hysteresis controller generates the switching pulses that are fed to the VSC. The reference three-phase voltage signals generated is compared by the three-phase DSTATCOM output voltages to generate the switching pluses of the IGBTs of the VSC. In hysteresis control, each phase is regulated independently [12]. The hysteresis band h is the difference between V_H and V_L ($h=V_H-V_L$). The hysteresis band is inversely proportional to the switching frequency of IGBTs. Figure 6 shows the scheme of Hysteresis voltage controller. The hysteresis voltage control has the advantage of variable switching frequency, very fast response and simple operation than other control method. In this method, the following relation is applied where h and fc are Hysteresis band and switching frequency, respectively.

$$h= V_H-V_L \tag{5}$$

$$T_1 + T_2 = Tc =1/fc \tag{6}$$

Where h is hysteresis band

V_H is upper voltage toleranance limit

V_L is lower voltage tolerance limit

T_1,T_2 are time periods of on and off cycles

Respectively

T is the total time period

When $V_o > V_H$, V_L is operated (7)

$V_o < V_L$, V_H is operated (8)

Where V_o is output voltage of the hysteresis band

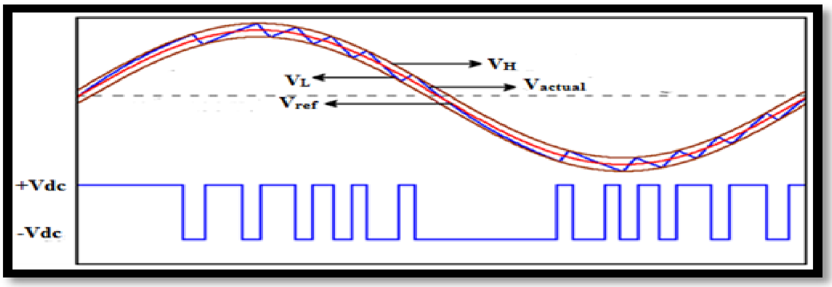


Figure 5. Principle of Hysteresis voltage controller

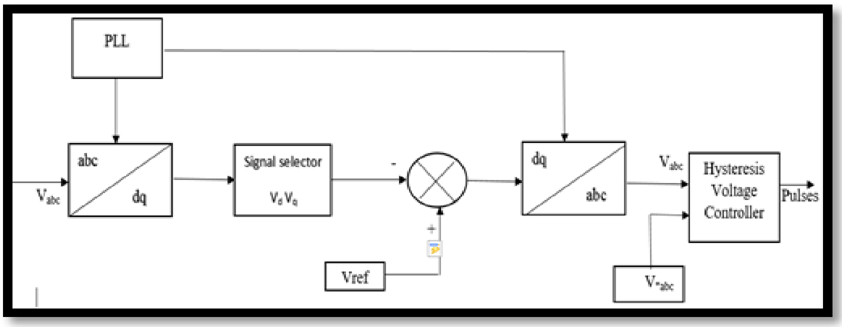


Figure 6. Block diagram of Hysteresis voltage controller

The voltages at PCC (V_{abc}) are converted to the rotating reference frame using the abc-dqo conversion .Phase Locked Loop, which synchronizes the positive sequence component of the three phase voltage. The abc_to_dq0 Transformation computes the direct axis (V_d), quadratic axis (V_q), and zero sequence (V_o) quantities in a two-axis rotating reference frame for a three-phase sinusoidal signal. Main voltages used as a Phase lock loop (PLL) to generate sine-wave single phase. The transformation is given below

$$Vd = \frac{2}{3} * \left(Va * \sin(wt) + Vb * \sin\left(wt - \frac{2\pi}{3}\right) + Vc * \sin\left(wt + \frac{2\pi}{3}\right)\right) \quad (9)$$

$$Vq = \frac{2}{3} * \left(Va * \cos(wt) + Vb * \sin\left(wt - \frac{2\pi}{3}\right) + Vc * \cos\left(wt + \frac{2\pi}{3}\right)\right) \quad (10)$$

$$Vo = 1/3(Va + Vb + Vc) \quad (11)$$

Since the dqo transformation is one that converts frequency dependent signals into ones with constant value, an ideal three phase system yields constants V_d and V_q. These voltage V_d and V_q are compared with a reference voltages and these are transformed to dq0 to abc transformation which is given to Hysteresis voltage controller block which is shown in Figure 46. The transformation is given below.

$$Va = (Vd * (wt) + vq * (wt) + Vo) \quad (12)$$

$$Vb = \left(Vd * \sin\left(wt - \frac{2\pi}{3}\right) + Vq * \cos\left(wt - \frac{2\pi}{3}\right) + Vo\right) \quad (13)$$

$$Vc = \left(Vd * \sin\left(wt + \frac{2\pi}{3}\right) + Vq * \cos\left(wt + \frac{2\pi}{3}\right) + Vo\right) \quad (14)$$

where w= rotation speed (rad/s) of the rotating frame.

Fuzzy logic controller

The Fuzzy logic controller is designed to control the load voltage. Controller consists of two sources such as error (change of supply voltage) and error rate (rate of change of supply voltage) and output (voltage). Five linguistic factors are choosen. The linguistic factors are Negative Big (NGB), Negative Medium (NGM), Zero (ZO), Positive Medium (PSM) and Positive Big (PSB). Triangular membership function is used. Twenty five if then rules are formed. The controller is designed by using a fuzzy logic toolbox in MATLAB/ SIMULINK. Table 1 shows the rule base of Fuzzy Logic Controller (25 rules) [13].

Table 1. Rule base of Fuzzy controller

de / e	**NGB**	**NGM**	**ZO**	**PSM**	**PSB**
NGB	NGB	NGB	NGB	NGM	ZO
NGM	NGB	NGB	NGM	ZO	PSM
ZO	NGB	NGM	ZO	PSM	PSB
PSM	NGM	ZO	PSM	PSB	PSB
PSB	ZO	PSM	PSB	PSB	PSB

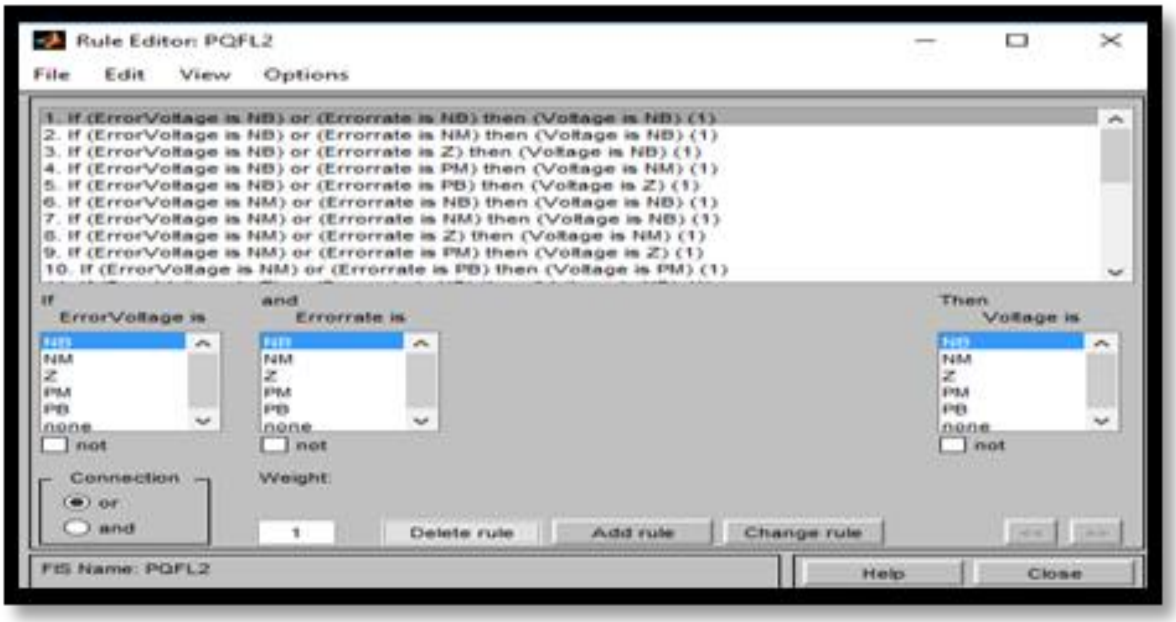


Figure 7. Rules of Fuzzy logic

Output of the model is processed with an error detector, and it is fed to a fuzzy logic controller. The output angle 'δ' of the controller is phase modulated depending on the controller actions. These signals in the form of pulses are provided to PWM generator and the output of the PWM generator will improve the performance of DSTATCOM during a voltage sag. Figure 8 shows the block diagram of the fuzzy logic controller.

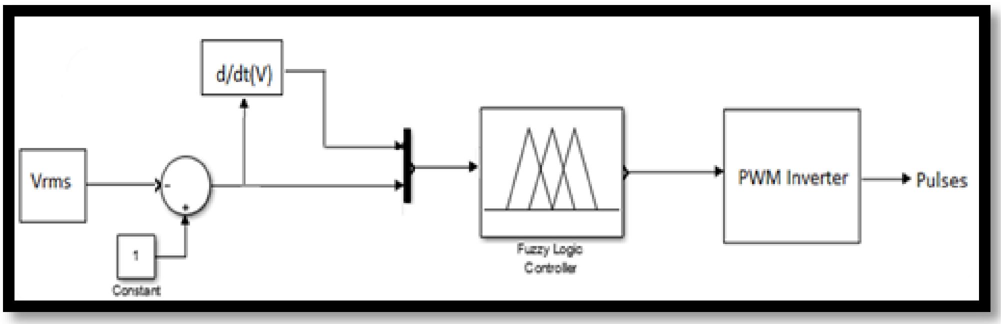


Figure 8. Block diagram of Fuzzy logic controller

4. Results and Discussion

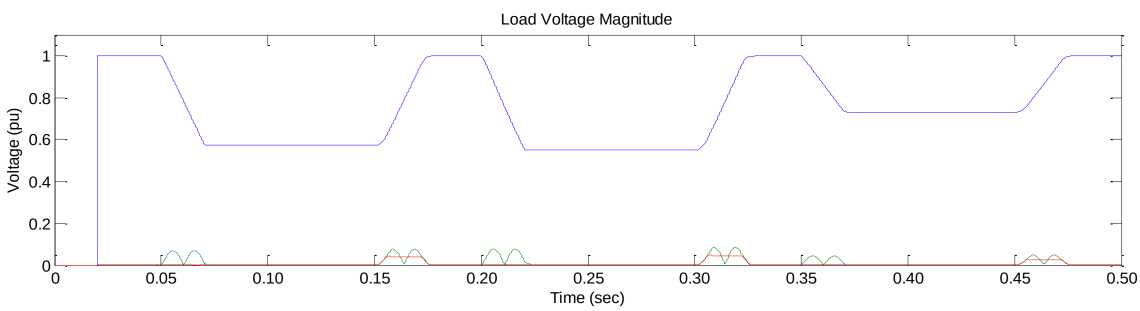
Simulation model of a DSTATCOM is developed for a three phase distribution system in MATLAB environment using SIMULINK and Sim Power System (SPS) toolboxes. The system voltage is 3.3 kV, 50 Hz and its ratings are shown in Table 2. In order to show the adequacy of this controller in providing constant voltage, simulations are performed for different types (a) without a controller and (b) with a controller. Simulation results are examined for different case studies and THD is calculated. For the simulation study a three phase programmable source is treated as primary distribution substation and the distribution line is treated as the lumped inductance in series with the resistance. A heavy inductive load is connected at required instants to study the performance of the DSTATCOM for the case of voltage sag conditions.

Table 2. Mine A Electrical Ratings

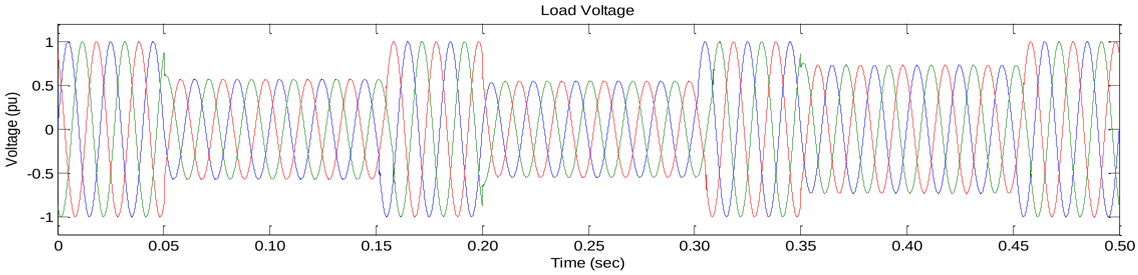
S. No	Name of the Equipment	Rating		
		Power	*Voltage*	*Current*
1	Transformer (TS2)	4.5 MVA	11 kV / 3.3 kV	236 A / 787.2 A
2	Shearer	855 kW	3.3 kV	2000 A
3	Armoured Face Conveyor (AFC)	860 kW	3.3 kV	2000 A
4	Beam stage loader(BSL)	400 kW	3.3 kV	2000 A

Without controller

In this section test system is first simulated without DSTATCOM in order to show the voltage sag problem. Voltage sag is observed in the system by connecting breaker to loads for certain time period. In this case, three loads are connected to the system from 0.05 s to 0.15 s, 0.20 s to 0.30 s and 0.35 s to 0.45 s which is shown in Table 3. A voltage sag occurs and there is no control over the system. Before compensation THD observed is 27% which is shown in Table 3 and simulation results are shown in Figure 9. We can observe from the load voltage output that, there are harmonics present in the system which are harmful to the system. In order to reduce sag and harmonics, we need to use controllers, these controllers are discussed in the next section. The load voltage magnitude observed is 0.55 pu.



(a) Three phase load voltage magnitude



(b) Three phase voltage

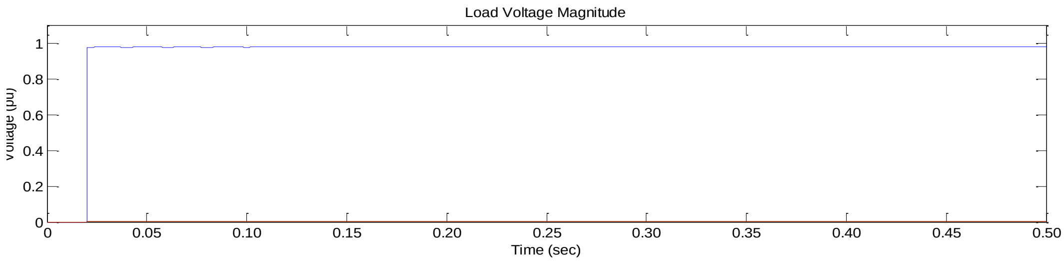
Figure 9. Simulation results without controller

a. With controller

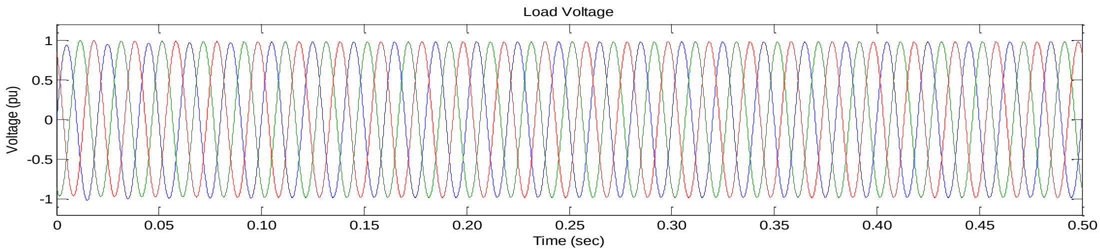
In this section, test system is simulated by employing DSTATCOM controlled by using three controllers such as PI controller,hysteresis voltage controller and fuzzy logic controller respectively.

i. PI controller

PI controller is used as a controller in the system and simulation results are shown in Fig.10 (a) three phase load voltage magnitude and (b) three phase load voltage. We can observe from the results that before compensation THD was 27% whereas after compensation THD reduced to 13.33 % which is shown in Table 3, but complete compensation is not achieved still there is voltage sag and harmonics present in the system which is undesirable. Therefore due to the present of voltage sag in the system reactive power compensation achieved is not satisfactorily. The load voltage magnitude observed from the results is 0.96 pu.



(a) Three phase load voltage magnitude

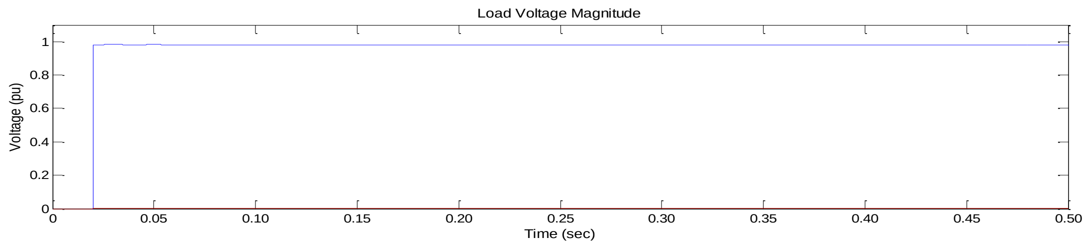


(b) Three phase voltage

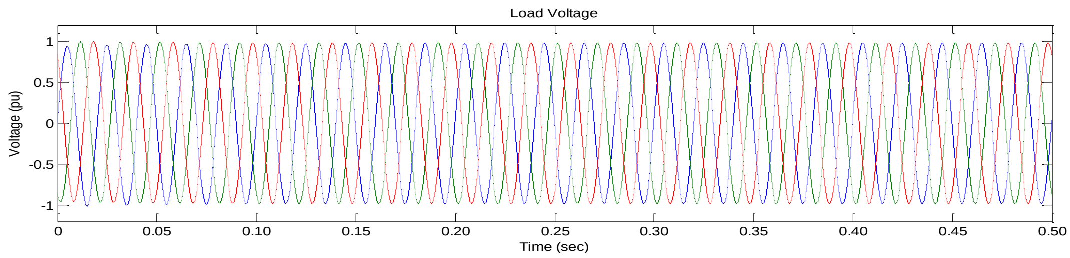
Figure 10. Simulation Results with PI controller

Hysteresis voltage controller

When this hysteresis voltage controller is introduced results show that THD is reduced to 5.37 % when compared to THD of PI controller which is given in Table 3 and simulation results are shown in Fig.11 (a) three phase load voltage magnitude and (b) three phase load voltage. We can observe from the results that hysteresis voltage controller is better than PI controller, but still there are harmonics present in the system. In this case reactive power compensation is found to be satisfactory when compared with PI controller. The load voltage magnitude observed from the results is 0.98 pu.



(a) Three phase load voltage magnitude

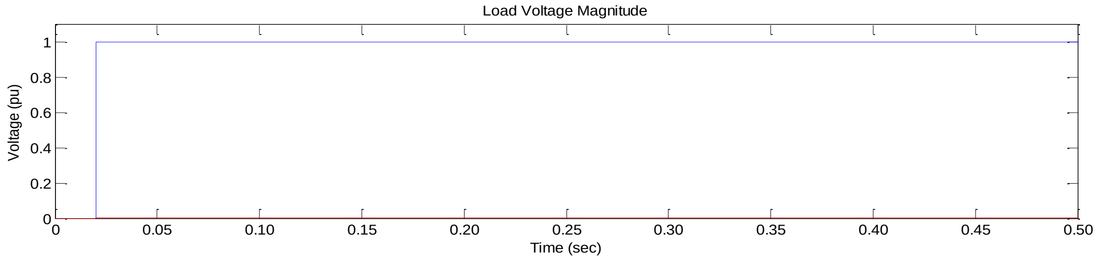


(b) Three phase load voltage

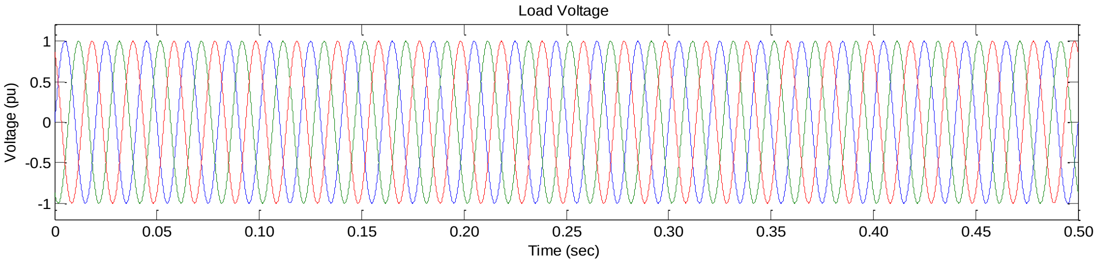
Figure 11. Simulation Results with Hysteresis voltage controller

Fuzzy logic controller

In this section, Fuzzy logic controller based DSTATCOM is introduced and results show that, THD is decreased to 1.51 % which is given in Table 3**.** Results are shown in Figure 12 (a) three phase load voltage magnitude and (b) three phase load voltage. We can observe from the results that mitigation of voltage sag compensation is achieved by using Fuzzy logic controller when compared with other two controllers. Fuzzy Logic Control based DSTATCOM is used to compensate reactive power and harmonics. The load voltage magnitude observed from the results is 1.0pu. The Fuzzy Logic Controller based DSTATCOM demonstrates a better dynamicbehaviour than conventional methods.



(a) Three phase load voltage magnitude



(b) Three phase load voltage

Figure 12. Simulation Results with Fuzzy logic controller

A comparative study is made between three different controllers for mitigating voltage sag. The comparative study is based on the THD of the load voltage which is given in Table 3.

Table 3. Comparasion of Parameters

Parameters	**Without controller**	**PI controller**	**Hysteresis controller**	**Fuzzy logic controller**
Reactive power compensation	No	Partial	Satisfactory	Complete Satisfactory
Performance under balanced and unbalanced loads	More Harmonics	Reduced Harmonics	Reduced Harmonics	Reduced Harmonics
THD	27 %	13.33 %	5.37 %	1.51 %
Load voltage (pu)	0.55	0.96	0.98	1.0

5. Conclusion

This paper presents the modeling and design of DSTATCOM for mitigation of voltage sag in underground coal mines .Three controllers like PI controller, Hysteresis voltage controller and Fuzzy logic controller are designed. Comparative analysis of THD and reactive power compensation for all three controllers shows that Fuzzy logic controller waveforms better in terms of harmonic reduction and compensation of reactive power. Simulation results are compared for DSTATCOM without a controller and with a controller. So from the results we can observe that voltage dip problem is mitigated as we compared with and without controller. It is observed that Fuzzy logic controller load voltage magnitude is 0.99 pu which is better than the use of other controllers in the system. It is clear from the above simulation studies that Fuzzy logic controller is more efficient in mitigating the voltage sag problem and also reactive power compensation is found to be satisfactory. The THD measured in the presence of a Fuzzy logic controller with DSTATCOM is within the IEEE standards. Maintaining constant voltage level results in higher productivity of the coal and also reliable and safety operation to the equipment connected to the supply system.

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