# Fuel Cell Integrated with Five Level VSI for Industrial Pump Applications

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**Abstract-** This paper investigates and analyses a Solid Oxide Fuel Cell (SOFC) connected three-phase five level voltage source inverter (VSI) supplying induction motor driven industrial pump systems. The neutral point clamped (NPC) topology is used for multilevel VSI and phase disposition switching frequency optimal pulse width modulation (PD-SFO PWM) technique is proposed for producing three-phase five level ac voltages. The output of VSI is used to drive three-phase induction motor driving a pump load system. Extensive studies have been carried out on the proposed novel system. The harmonic analysis of the proposed multilevel VSI output is also evaluated to assess the power quality. The proposed model is implemented in MATLAB/SIMULINK environment to obtain the results under different operating conditions, which thereby validates the proposed system model.

**Keywords-** Five level inverter, Induction motor drive, PD-SFO PWM, Pump load, Solid Oxide Fuel Cell (SOFC).

## 1. Introduction

Rapid growth in energy consumption during the last century is increased many folds, while depleting resources of energy has caused many concerns and issues nowadays. Although the conventional sources of energy, i.e. fossil fuels are limited and sooner or later will vanish. The fossil fuels are also creates serious environmental hazards. Therefore, pollution free sustainable sources of energy are needed and fuel cell technology is one of them.

Nowadays Fuel cell is gaining attention from the researchers due to rapidly developing electricity generation technology. In it chemical energy is converted into electrical energy directly. The fuel cell generates dc power when hydrogen rich gases passes over anode and oxygen over cathode and an electrolyte introducing in between to enable exchange of ion [1]. Fuel cell technology has several advantages, such as moderate efficiency (35-65%) [2], low emissions, high reliability, quiet operation and suitability to operate in remote areas [3][4]. The dc power generated by fuel cell needs to be converted into an ac power for application to drive three phase induction motor driven pump systems, which are commonly used in mining industries, heavy cooling towers, water treatment plant, steel plant, ash possessing in power plant, Minerals processing/copper & aluminium industry, chemical industries etc. [5].

Multilevel voltage source inverter (VSI) is a good choice to employ for ac systems [6]. The lower harmonic distortion in output voltage, lower *dV/dt* stress in load side [7] etc. are few advantages to mention [8][9]. Well established multilevel inverter topologies are neutral point clamped (NPC), flying capacitor (FC), cascaded H-bridge (CHB) [10]. These topologies are widely used in industries requiring medium and high electric power.

In this paper neutral point clamp (NPC) inverter topology is proposed for generation of five level ac voltage [11] and Multilevel phase disposition switching frequency optimal pulse width modulation (PD-SFO PWM) technique is used to provide gate pulses for IGBTs (insulated gate bipolar transistor) used in five-level NPC inverter. This five level NPC inverter is used to supply ac power to a three-phase induction motor-pump system.

The induction motor has several advantages in comparison to DC motor such as better ruggedness, inexpensive, more reliable and robust etc. [12]. In most of the cases induction motor is used to drive the industrial pump systems. Centrifugal pump are the most common type of kinetic pump, and it is widely used in the field of irrigation and industrial fluid pumping applications. Centrifugal pumps are more economical to operate and require lesser maintenance then other types of pumps.

Few papers are reported on proposed concept in literature. Savitha *et al* [13] proposed five-level multi-string inverter for full cell application however the inverter used in this paper is suggested for low power applications only. García *et al* [14] proposed the concept of voltage harmonic compensation control for a stand-alone fuel cell-single phase inverter supplying both linear and nonlinear load. Bojoi *et al* [15] proposed dual-source fed multiphase induction motor drive for fuel cell operated vehicles. This system is proposed for 10 kW, 40V, 12-poles, 200 Hz, induction motor load. It is evident from the literature that fuel cell-multilevel inverter has not been proposed for large power industrial fluid pump systems normally used in coal mine etc.

In this paper, performance analysis of SOFC connected multilevel NPC inverter supplying induction motor driven industrial pump system is investigated in detail. The advanced PD-SFO PWM technique is proposed to generate the five levels in output ac voltage. The complete system is analyzed under different loading conditions.

## 2. System Description

The Complete system is divided into three major parts a) Solid Oxide Fuel Cell, b) Three-phase five-level NPC -VSI along with modulation technique, c) three-phase Induction motor drive industrial pumping system. The Various components of system are described as;

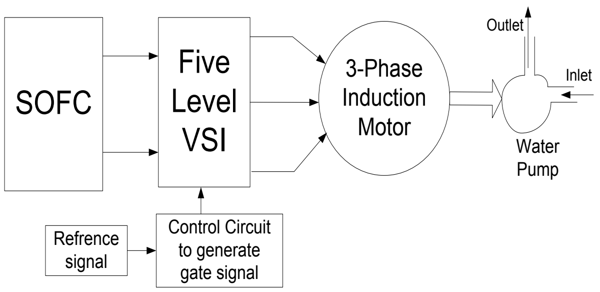


**Fig. 1.** Schematic diagram of complete system

The block diagram of complete system model is shown in “fig.1”. The SOFC is used for electric power generation. SOFC generate dc power and it needs to be converted into an ac power for driving three-phase induction motor coupled pump system. For this purpose use of a three-phase five-level NPC VSI is proposed to convert dc power into ac power which also controls the frequency according to load demand. Here three-phase squirrel cage Induction motor coupled with the industrial pumping system is used in remote area applications.

### *2.1. Solid Oxide Fuel Cell (SOFC) System Model*

The SOFC system model [16] [17][18] is shown in “fig.2”, in this model following assumptions have been considered: i. the fuel cell gases are ideal ii. the fuel cell temperature is invariant. The related mathematical model equations are summarized as:

a) The chemical reaction of *CO* and $H_2O$ generate hydrogen and carbon dioxide. The *CO*-shift reaction is given as [19]:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (1)$$

For this model it is assumed that only $H_2$ and $O_2$ enter into the fuel cell.

b) Fuel utilization is the ratio of fuel flow that reacts “ $q_{H_2}^r$ ” and input fuel flow “ $q_{H_2}^{in}$ ”:

$$U_f = q_{H_2}^r / q_{H_2}^{in} \qquad (2)$$

Here fuel utilization is considered as 80-90% and $q_{H_2}^r$ is defined as:

$$q_{H_2}^r = \frac{N_0 I_{fc}^r}{2F} = 2K_r I_{fc}^r \qquad (3)$$

The demand current of the fuel cell system “ $I_{fc}^{in}$ ” is resulted in the following range:

$$\frac{0.8 q_{H_2}^{in}}{2K_r} \le I_{fc}^{in} \le \frac{0.9 q_{H_2}^{in}}{2K_r} \qquad (4)$$

c) The real current output in fuel cell can be measured, so the fuel flow input can be controlled by controlling of $U_f$ at average value of *85%*, hence

$$q_{H_2}^{in} = \frac{2K_r I_{fc}^r}{0.85} \qquad (5)$$

d) The maximum power capacity of the fuel cell is the ratio between maximum theoretical power delivery and rated power. For higher efficiency and dynamic load, $p_k$ should be as large as possible. For prevention of damage to the electrolyte, the pressure difference between the hydrogen and oxygen gas compartment should be below 8 kPa under transient condition and 4 kPa under normal conditions [18].

e) The overall fuel cell reaction is:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \qquad (6)$$

The electrical response time of fuel cell is fast and mainly depends upon the speed at which chemical reaction is capable to restoring the charge that has been drained by the load. The dynamic response of fuel cell is a first order transfer function with a time constant 0.8 s. The parameters of SOFC are given in Table-I of appendix.

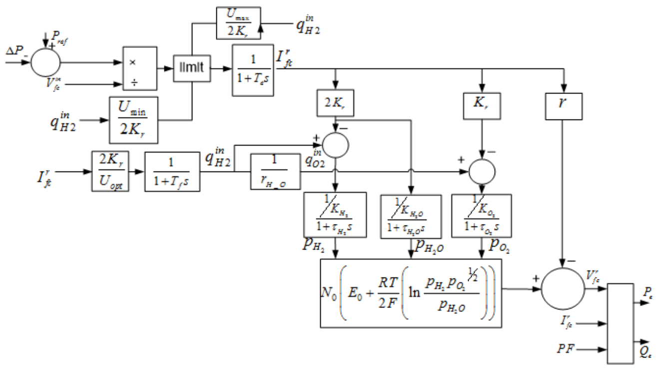

**Fig. 2.** SOFC mathematical model

*2.2. Three Phase Five Level NPC-VSI Topology Along with Modulation Technique*

In this paper NPC topology [20] is proposed for generation of three-phase five-level voltage. Four capacitors (C) are connected in parallel with the dc voltage source for this topology. Hence $V_{dc}/4$ voltage appears across each capacitor. The connection diagram of NPC-VSI is shown in "fig.3". For multilevel inverter, in order to generate n-level, it needs (n-1) carrier waves. Sa1 – Sa4 are the positive side connected IGBTs and Sa1' – Sa4' are the negative side connected IGBTs for lag 'a'. Similarly devices are connected for lag 'b' and lag 'c'. Terminal A, B and C are the output for phase 'a', 'b' and 'c' respectively.

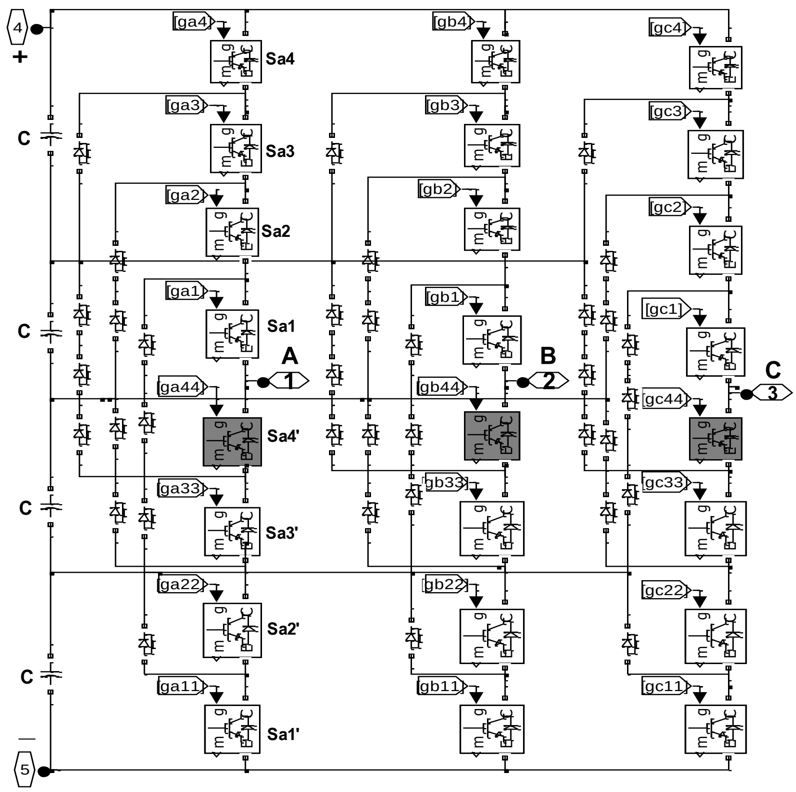


**Fig. 3.** NPC topology

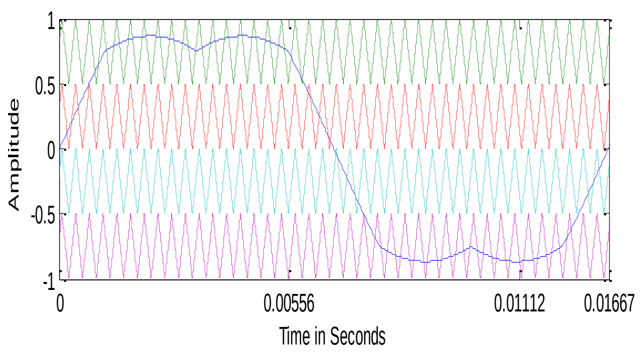


**Fig. 4.** PD-SFO PWM Modulation

In PD-SFO PWM technique multilevel triangular carrier waves are phase disposition and the reference signal ($V_aSFO$, $V_bSFO$, $V_cSFO$) is generated by taking instantaneous average of the maximum and minimum of the three reference sine wave signal ($V_a$ ,$V_b$, $V_c$) and displaced each-other by $120^0$, and subtract the $V_{offset}$ value from each of the reference signal to generate the modulation waveform [21].

$$V_{offset} = \left[ \frac{\max(V_a, V_b, V_c) + \min(V_a, V_b, V_c)}{2} \right] \tag{7}$$

$$V_aSFO = V_a - V_{offset} \tag{8}$$

$$V_bSFO = V_b - V_{offset} \tag{9}$$

$$V_cSFO = V_c - V_{offset} \tag{10}$$

Eq.(8), (9) and (10) are compared with multilevel triangular carrier waves which generates the output PWM pulses as shown in "Fig. 4".

### *2.3. Induction Motor Driven Industrial Pump System*

In this section the centrifugal pump is driven by a three phase induction motor. The data of standard pump curve of A.W. CHESTERTON CO. is taken for the calculation of BHP (brake horsepower) for different mode of operation [22].

- Pump Size: 3 × 4 - 13
- Pump Speed: 3550 rpm
- Specific Gravity: 1.2
- Impeller Diameter: 11 inches
- Discharge Gauge Pressure: 290 psig
- Discharge Gauge Height from Shaft Centerline: 3 ft.
- Suction Gauge Pressure: 30 psig
- Suction Gauge Height from Shaft Centerline: 1 ft.

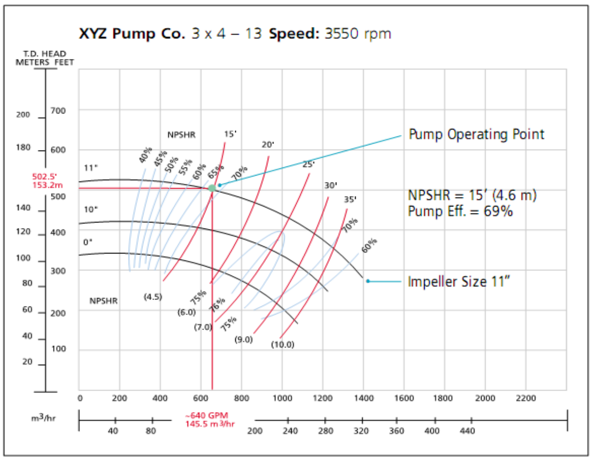


**Fig. 5.** Pump performance curve

The differential pressure for this pump is calculated as:

Differential pressure = Discharge Gauge Pressure - Suction Gauge Pressure

Here, Differential pressure = 290-30 = 260 Psi

$$\text{Head(ft.)} = \frac{\text{Pressure(Psi)}\times 2.31}{\text{Specific Gravity}}$$

Differential head =260 × 2.31/1.2 = 500.5 ft.

Actual point of operation = 500.5 ft. + (3-1) ft. = 502.5ft.

= 153.2m

From the fig.5, estimated capacity 640GPM (145 m3/hr), at this point the pump efficiency is 69%.

Power required for this pump:

$$\text{BHP} = \frac{\text{Capacity (GPM)}\times\text{Head (ft.)}\times\text{Specific Gravity}}{\text{Pump efficiency}\times 3960}$$

$$\text{BHP} = \frac{640\times 502.5\times 1.2}{0.69\times 3960}$$

BHP=141.2HP (105.4 kw)

Torque generated by pump (T) = BHP/ω

T= 283.52 N*m

## 3. Simulink Model of Complete System

The simulation model of complete system is shown in "fig.6". The SOFC is used as a power supply system, which generates dc power and is fed to dc link of three-phase five-level inverter to produce three-phase ac power at 60Hz. The output of VSI is fed to induction motor coupled pump. Here, gear system is used for increasing the speed of pump which is coupled with induction motor. Pump used in this study is running at 3550 rpm whereas the induction motor is running at 1787 rpm. The parameters of induction motor are given in Table-II of appendix.

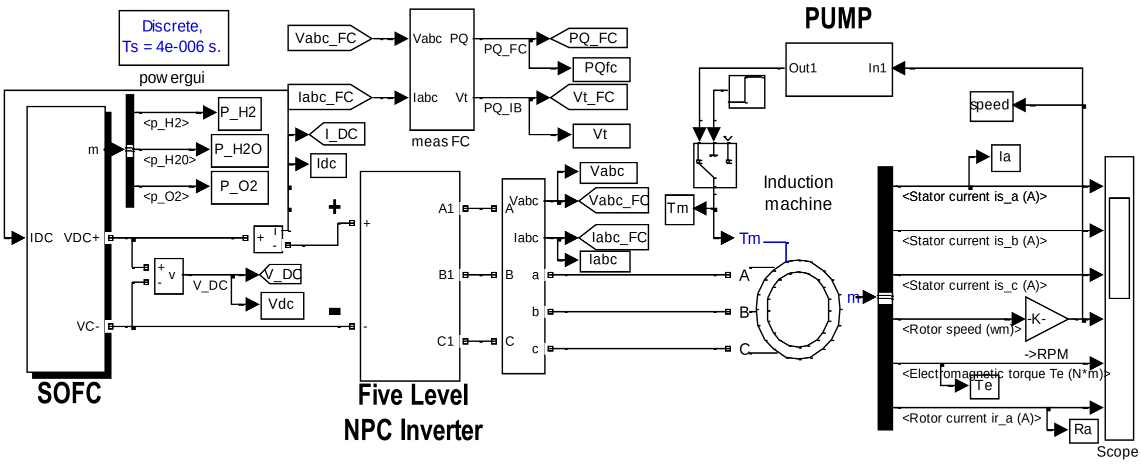


**Fig. 6.** Complete simulation model2.

## 4. Result and Discussion

The parameters of SOFC and induction motor are summarized in appendix. “Fig.7”. presents the pressure of hydrogen ($P_{H2}$), water ($P_{H2O}$) and oxygen ($O_2$) in kPa. “Fig.8”. shows that dc link voltage and current waveforms. At starting induction motor is running at no-load and the pump load is connected with the motor at 1.4 seconds as shown in “fig.9”. During starting period the induction motor draws high amount of current, the induction motor starting period is approx. 1 second. After 1 second the motor is achieving its full speed at no load. The no load electromagnetic torque ($T_e$) is approximately zero as evident from “fig.9”. $I_{sa}$ and $I_{ra}$ represent the stator and rotor phase ‘a’ current respectively. When pump load is connected at 1.4 second the stator and rotor current increases correspondingly. The electromagnetic torque is also increased. For this system the electromagnetic torque is 285 N*m approx. when the pump load is connected to the system and it takes around 0.2 seconds to achieve the steady state. “Fig.10” represents the applied mechanical pump torque and speed of induction motor. At starting the induction motor is operated at no-load, hence the mechanical torque is zero and at 1.4 seconds the pump load is connected hence the mechanical torque 283.52 N*m is applied at this time. The motor no-load speed is 1785 rpm and at pump load the motor speed is reduced to 1777 rpm.

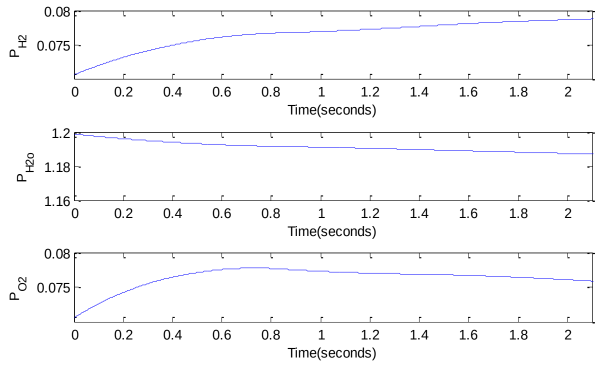


**Fig. 7.** Pressure of $H_2$ , $H_2O$ and $O_2$

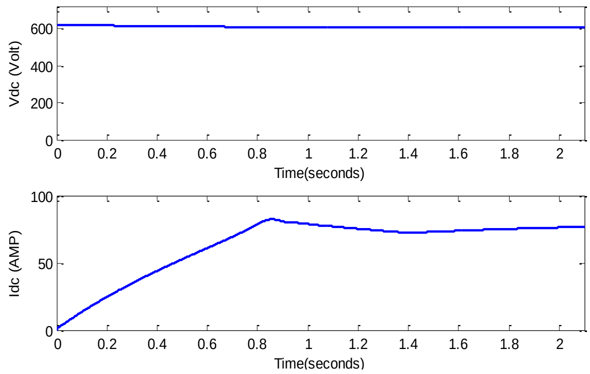


**Fig. 8.** DC link voltage and current

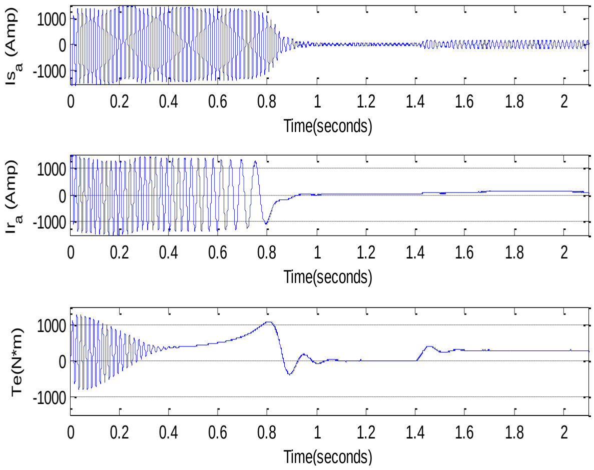


**Fig. 9.** Stator current, rotor current and Electromagnetic torque

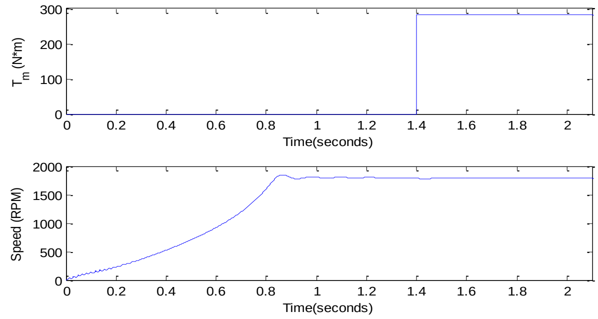


**Fig. 10.** Mechanical torque and motor speed

“Fig.11” represents the three-phase voltage and current waveforms. At starting period (0-1 second) the motor takes large current while when motor runes at full speed at no load (1-1.4 seconds) the motor takes smaller current, during connection of pump load the current is increased during loading period (1.4 seconds - 2.1 seconds). The fig.12 represents the three phase current ($I_{abc}$) and voltage ($V_{abc}$) waveforms for one cycle during pump load. The five steps in voltage is counted as 0, $+V_{dc}/4$, $+V_{dc}/2$, $+3V_{dc}/4$ and $+V_{dc}$ as shown in “fig.12”.

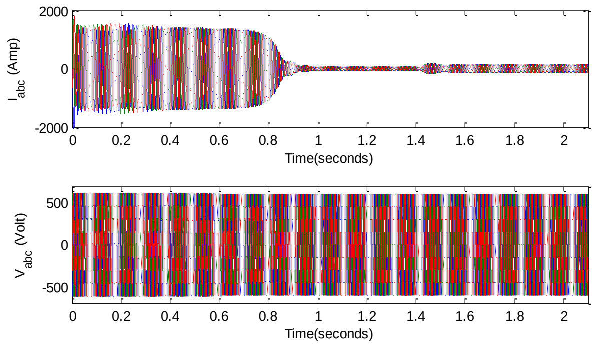


**Fig. 11.** Three-phase current and voltage

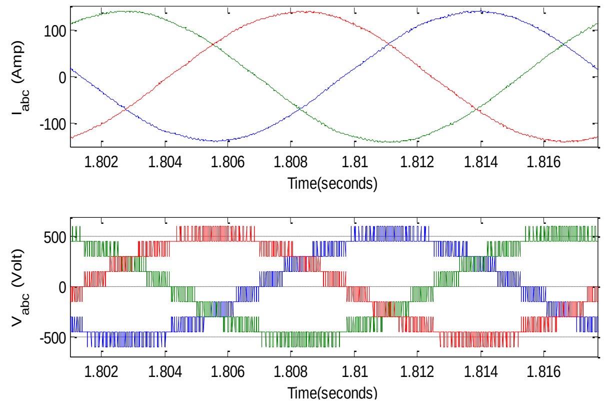


**Fig. 12.** Three-phase current and voltage

The harmonic analysis of the output voltage waveform of proposed five-level NPC-VSI is carried out to assess the effect on power quality of the system:

From “fig. 13”, it is seen that second harmonic component 0.34%, third harmonic component 0.42%, fourth harmonic component 0.08%, fifth harmonic component 0.25%, sixth harmonic component 0.41%, seventh harmonic component 0.13%, ninths harmonic component 0.12%, eleventh harmonic component 0.03%, thirteenth harmonic component 0.04% are recorded in it

The THD of the proposed five-level inverter is 17.11% for one cycle as shown in “fig.13”.

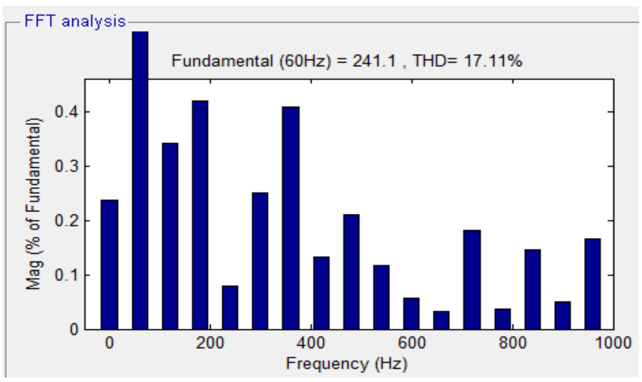


**Fig. 13.** THD of Vab voltage for one cycle

## 5. Conclusion

The performance analysis of a SOFC-five level VSI has been carried out for feeding industrial pump system. The each component of the system has been modeled and integrated in Matlab/Simulink. The advanced PD-SFO PWM technique has been proposed for generating the gating pulses of VSI. The simulation has been carried out for different loading conditions. The results prove that the proposed system having NPC-VSI has been working satisfactory for large power industrial applications without any distortion in waveforms. The THD analysis has been also carried out for power quality point of view.

## Appendix

**Table 1.** Fuel Cell

| S.No. | SOFC | |
|---|---|---|
| | ***Parameters*** | ***rating*** |
| 1 | Absolute Temperature | 1273 K |
| 2 | Initial Current | 100 A |
| 3 | Faraday’s constant | $96.487\times10^{6}$ J/kmol |
| 4 | Universal gas constant | 8314 J/(kmol K) |
| 5 | Ideal Standard potential | 1.18 (V) |
| 6 | Number of cells in series | 650 |
| 7 | Maximum fuel utilization | 0.9 |
| 8 | Minimum fuel utilization | 0.8 |
| 9 | Optimal fuel utilization | 0.85 |
| 10 | Valve molar constant for hydrogen, water and oxygen | $8.43\times10^{-4}$, $2.81\times10^{-4}$, $2.52\times10^{-3}$ kmol/(s atm) |
| 11 | Ohmic loss per cell | $3.2813\times10^{-4}$ Ω |
| 12 | Electrical response time | 0.8 sec. |
| 13 | Fuel processor response time | 5 sec. |
| 14 | Ratio of hydrogen to oxygen | 1.145 |

**Table 2.** Induction Motor

| S.No. | Squirrel-cage induction motor | |
|---|---|---|
| | ***Parameters*** | ***Rating*** |
| 1 | Nominal power | 105.4 KW |
| 2 | Line-Line Voltage | 460 Vrms |
| 3 | Frequency | 60 Hz |
| 4 | Stator resistance and inductance | 0.0302 Ω, 0.000283 H |
| 5 | Rotor resistance and inductance | 0.01721 Ω, 0.000283 H |
| 6 | Mutual inductance | 0.01095 H |
| 7 | Pole pair | 2 |

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