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# Modelling and control of permanent magnet synchronous generator based on three level NPC using fuzzy PI

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*Abstract*— **Recently, the permanent magnet synchronous generator (PMSG) has been gained attention by wind turbine (WT) manufactures due to advance of control system and power electronics. The permanent magnet synchronous generator based on three level neutral point control (NPC) system using fuzzy logic control proportional integral (FLC PI) is proposed in this study. The NPC systems of DC link are implemented more easily than two level systems. The NPC systems provide better harmonic reduction than conventional two level voltage source converters. The control strategies of the NPC systems reduce semiconductor losses. The proposed system can be implemented to the multi-level converters above three-level. The proposed system is developed using the steady state technique. The performance of the PMSG system under variation operation condition is investigated in this study and the performances of the PMSG based on three level NPC using FLC PI are analyzed. The validity of the proposed system is implemented and verified in the MATLAB/Simulink using three-level insulated gate bipolar transistor (IGBT) converter.**

*Index Terms*— **Permanent magnet synchronous generator (PMSG), wind turbine (WT), neutral point control (NPC) systems.**

## I. Introduction

RECENTLY, PMSG has been gained attention by wind turbine (WT) manufactures owing to improvement of control system and power electronics [1]. The variable speed WT provides more effective power available than constant speed. Therefore, the WT enhances to operate at variable speed value [2,3]. A control system is improved to available maximum power from the WT [4,5]. In addition, the control system supplies to required fixed frequency and voltage for the grid. Therefore, the PMSG is used for high efficiency and controllability in the variable speed WT systems [6]. The PMSG can be connected to the electrical grid by GSC systems [7]. However, these power electronic converters cause harmonic distortion for electrical grids.

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In this study, a grid side converter for variable speed PMSG based on three level NPC is proposed. Three level NPC system has implemented to high power wind energy conversion system (WECS). One of the most important characteristics of the three level NPC system is providing better harmonic reduction than conventional two level voltage source converter. The control strategies of the NPC system reduce semiconductor losses. The aim of this paper is the controlling and dynamic modelling of WECS based on the PMSG. Moreover, both MSC and GSC system based on three-level NPC using FLC PI control are designed for the load systems. The validity of the proposed system is implemented and verified by MATLAB/Simulink using three-level NPC system.

The rest of the paper is organized as follows; Section 2 introduces of each element of the wind power system. The mathematical model for PMSG is introduced in Section 3. Block diagram of proposed PMSG based on WECS is given in Section 4. The simulation results of proposed protection system are presented in Section 5. Finally, conclusions are given in Section 6.

## II. Dynamic Model of Wind Turbine

This section introduces mathematical model for each element of the wind power system, composed of WT, drive train, PMSG, electric grid, as given in Fig. 1. The PMSG is utilized as wind turbine generator type in this study. The PMSG without gearbox link to wind turbine and connected to electrical grid.

### A. Wind turbine

Wind turbine converts wind power into mechanical rotate power. The wind turbine consists a classic three-bladed horizontal-axis. Used model in this paper has aerodynamic behaviors of wind turbine. Mechanical power obtained from wind turbine can be described as in Eq. (1) [1].

$$P_m = \frac{1}{2}\rho A C_p(\lambda,\beta)v^3 \tag{1}$$

where $\rho$ depicts the air density, A shows the area swept by a classic three-bladed horizontal-axis, $v$ is wind speed, $\lambda$ and $C_p$ denote the wind turbine blade tip speed ratio and power coefficient, respectively. $\lambda$ expressed the aerodynamic behaviors of the WT. The power coefficient $C_p$ depicts a nonlinear function of the blade pitch angle $\beta$ and the tip-speed ratio $\lambda$ [1].

A wind turbine operates a wide range of wind speed value. Due to being very complex of the aerodynamic system in this operation conditions, results are difficult obtained as analytical.

### *B. Drive train for PMSG*

The drive train of variable speed WECS is composed of the hub with blades, a rotor shaft, a blade-pitching mechanism with a spinner, and generator. The electromechanical torque is obtained from PMSG and the aerodynamic torque is acquired from rotor in the WT. Torque equations are given in Eq. (2) and Eq. (3) [1].

$$T_m = \frac{P_m}{\omega_r} \tag{2}$$

$$T_e = \frac{P_e}{\omega_e} = \frac{2}{P}\frac{P_e}{\omega_r} \tag{3}$$

In general, the mechanical equation of a PMSG is given in Eq.(4).

$$J\frac{d\omega_r}{dt} = T_m - B\omega_r - T_e \tag{4}$$

where $\omega_e$ represents electrical angular frequency of PMSG, $P$ shows pole number of PMSG, $J$ denotes inertia moment of PMSG and $B$ is friction coefficient of the PMSG.

## III. Mathematical Model of PMSG

The mathematical model of PMSG can be used to simulate entire system. This model is required to control methods of the PMSG. This model aims to solve control problems as theoretical and analytical [1,4].

Two phase coordinate reference *dq* frame is quite simple according to real three phase *abc* frame. The *dq* frame has dc quantities under steady-state operation, while the *abc* frame appears as sinusoidal quantities. Therefore, two phase coordinate reference *dq* frame is widely used to control and simulation purposes rather than real three phase *abc* frame at reference rotate speed. Linear equations are obtained using the mathematical facilitation. Additionally, these equations simplify the decoupled control of active power and reactive power in three-phase systems [8].

The hysteresis losses, skin effect, magnetic saturation, and stator core losses are neglected in the most widely accepted PMSG model. PMSG voltage equations are expressed by[9]:

$$v_{sd} = R_s i_{sd} + L_d\frac{di_{sd}}{dt} - \omega_e\psi_{sq} \tag{5}$$

$$v_{sq} = R_s i_{sq} + L_q\frac{di_{sq}}{dt} + \omega_e\psi_{sd} \tag{6}$$

If the *dq* axes rotate at the synchronous speed and the *d*-axis is aligned with the rotor flux, the stator flux components are given by [9]:

$$\psi_{sd} = L_d i_{sd} + \psi_f \tag{7}$$

$$\psi_{sq} = L_q i_{sq} \tag{8}$$

As a result, the voltage equations in the *dq* synchronous reference frame are given as follows [9]:

$$v_{sd} = R_s i_{sd} + L_d\frac{di_{sd}}{dt} - \omega_e L_q i_{sq} \tag{9}$$

$$v_{sq} = R_s i_{sq} + L_q\frac{di_{sq}}{dt} + \omega_e L_d i_{sd} + \omega_e\psi_f \tag{10}$$

## IV. Proposed System for PMSG

Block diagram of proposed PMSG based on WECS is given in Fig. 1. A WECS based on PMSG consists of a WT connection to a drive train, a MSC connected with stator of PMSG and a GSC connected with the load. Three level NPC is utilized for MSC and GSC. The diode clamped topology is exploited for three level NPC in this study. The inputs of the PMSG are connected to drive train, blade and other mechanical systems in wind turbine. The outputs of the generator are connected to a MSC, DC link, a GSC, and load in the WECS, respectively.

### *A. Machine side converter and controller*

The MSC and GSC scheme based on three levels NPC for PMSG is illustrated in Fig. 1. Three level NPC system has implemented to high power WECS. One of the most important characteristics of the three level NPC system is providing better harmonic reduction than conventional two level voltage source converter. The control strategies of the NPC system can reduce semiconductor losses. In order to achieve three steps in output AC voltages, two capacitors are employed in the three level NPC system [10].

Control block diagram of the MSC is given in Fig. 1. The controller structure of the MSC consists of two loops such as d and q loops controller. The operation of the MSC requires *d* and *q* loops of the reference frame that are determined by sustaining output of the stator and the output active power. For the reactive power compensated, stator current is controlled by *d* and *q* loops of the reference frame in the unity power factor control system. For generated maximum power torque of the generator, stator current in the maximum torque is controlled by only *q* loop [11,12]. However, rated power of the generator is surpassed due to the reactive power is not adjusted. The voltage waveforms of the MSC are acquired by equating the *d* and *q* loops of both reference and actual current values. The voltage waveforms are supplied voltage source PWM to maintain a constant switching frequency [12].

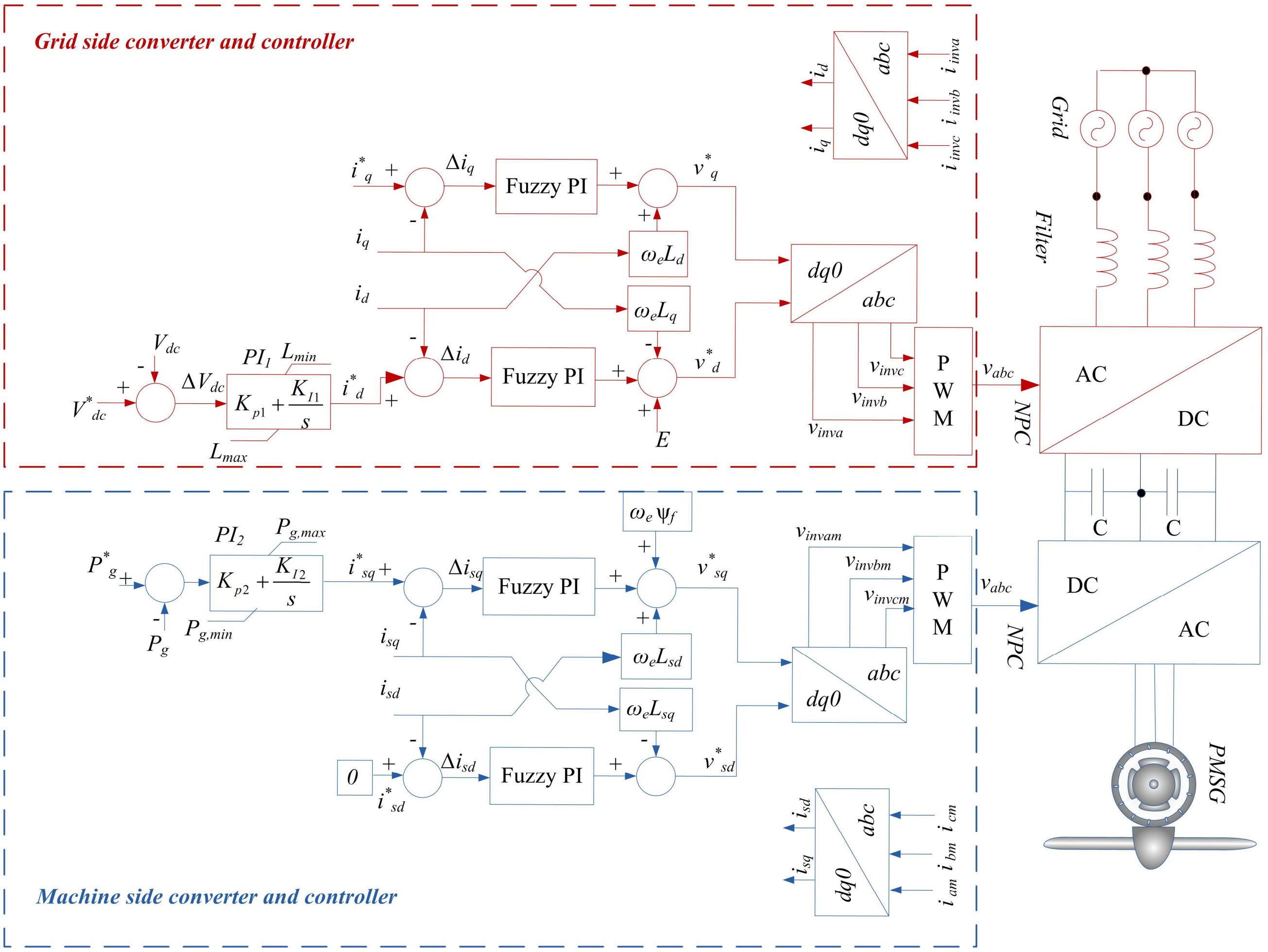


Fig.1. Permanent magnet synchronous generator system based on WECS

### B. *Grid Side Converter and Controller*

The GSC consists three level NPC system, with three legs. For one per phase of the NPC system is used two series connected IGBT and anti-parallel diodes. Three level half bridge power module using IGBT are implemented to proposed system. This power module has two topologies: a switched topology and a control topology. A switched topology uses the semiconductors using three level NPC system. A control topology uses controlled current sources using PI control system.

In the control topology, a GSC control system implemented as a PI regulator provides a current set point to an inner *dq* current controller as shown in Fig. 1. The current controller measures the DC voltage and calculates the error compared to the $V_{dc}$ reference value. The current controller has separate PI regulators for direct and quadrature currents that produce a *dq* reference [10,11]. The AC phase voltages and currents are measured and fed to the current controller. A phase-locked loop generates the reference phase angle for the *abc* to *dq* transformations. A low pass filter is inserted into the feedback path from the $I_{a,b,c}$ measurement to represent the limited bandwidth of the current sensor. Modulation indices are generated for each of the three separate modulators for the three phase legs.

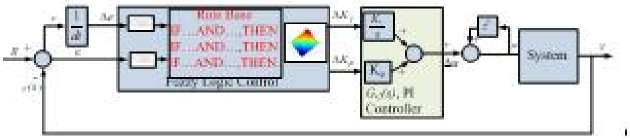
### C. *Fuzzy logic-PI controlle*

Conventional PI control method is widely implemented in wind turbine systems owing to its simple structure. The PI control method forces the system to achieve the optimum values by using the two gain parameters. Therefore, PI equations are expressed by Eq. (11):

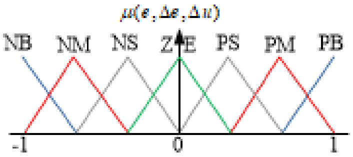
$$u(k) = K_P e(k) + \frac{K_P T_s}{T_I} \sum_{i=0}^{k-1} e(k) \qquad (11)$$

where, $K_P$ and $K_I$ are proportional gain, integral gain, respectively. The *e(k)*, $T_S$, and $T_I$ is the error, the sampling period, the integral time constant, respectively. In addition to these, maximum overshoot of the system, steady-state error, and the time response features of rise time is fixed by conventional controller.

In general, conventional controller method has non-linear for parameter variations under load variation. When parameter variations come about in different operational conditions, the conventional control system can not resolve the error of the wind turbine system. Therefore, Fuzzy PI control is presented to improve system robustness in this study. Fuzzy PI control is implemented both GSC and MSC for wind turbine based on PMSG. The general block diagram of fuzzy PI control method is given in Fig 2.




a)




b)

Fig.2. a) The general block diagram of fuzzy PI control method. b) MFs of e, Δe , and Δu

The fuzzy sets of FLCs are divided into seven sections for the input and output variables that consist of seven variables in the proposed study. These seven variables are named as Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB) [13].

The centroid defuzzification technique is given in Eq.(12).

$$y = \frac{\sum_{i=1}^{m} y_i + \mu_i(y_i)}{\sum_{i=1}^{m} \mu_i} \qquad (12)$$

Where, $y$, $m$, $y_i$ are the defuzzified output, the output quantificational index, and the output variable. $\mu_i(y_i)$ is the membership function.

Therefore, the rules of the FLC are obtained according to these principles, as given in Table 1. [13].

**Table 1.** Rule bases for e, Δe, Δu

| Δe / e | NB | NM | NS | Z | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | PB | PB | PB | PS | Z | Z | Z |
| NM | PB | PB | PB | PS | Z | Z | NS |
| NS | PB | PB | PB | Z | Z | NS | NS |
| Z | PS | PS | PS | Z | NS | NS | NM |
| PS | Z | PS | Z | NS | NM | NM | NB |
| PM | Z | Z | NS | NM | NB | NB | NB |
| PB | Z | NS | NM | NB | NB | NB | NB |

## V. Simulation Results

The simulation results of PMSG using three level NPC are presented in this section. The proposed model is designed to deliver power to a load. The presented simulations are realized for an 850-kW PMSG using three level NPC. The proposed model system is modelled and analysed in the Matlab/Simulink. The proposed model is proven to verify under different load conditions.

The proposed system is implemented varying load conditions. From time $t$=0s to $t$=2s, from time $t$=4s to $t$=6s, and from time $t$=8s to $t$=10s, the load value is 0.5 pu operation. The time $t$=2s to $t$=4s, the load value increases to 0.1 pu operation. From time $t$=6s to $t$=8s, the load value increases to 0.75 pu operation conditions.

The rotor speed is given in Fig. 3. When load value changes between 1 pu, 0.75 p.u and 0.5 pu, rotor speed remains a constant 1 p.u value. The DC link voltage ($V_{dc}$) is illustrated in Fig. 4. When load value changes between 1 pu, 0.75 p.u and 0.5 pu, the DC link voltage remains a constant 500V.

The active power of PMSG and load are given in Fig. 6 and 7, respectively. When load value changes between 0.5 pu and 0.1 pu, the active power value of PMSG and load change between 0.5 p.u and 1 p.u, respectively. The active power value of PMSG changes same with varying load.

The stator current of PMSG (rms) is given in Fig. 8. When load value changes between 0.5 pu and 0.1 pu, the stator current of PMSG changes between 0.5 p.u and 1 p.u, respectively. The stator current value of PMSG changes same with varying load.

The stator voltage of PMSG (rms) and load voltage are given in Fig. 9 and 10, respectively. When load value changes between 1 pu, 0.75 p.u and 0.5 pu, the stator voltage of PMSG and load voltage remains a constant 1 p.u.

The load current is given in Fig. 11. When load value changes between 0.5 pu and 0.1 pu, the current of load changes between 0.5 p.u and 1 p.u, respectively.

The total harmonic distortion (THD) of the proposed system is given in Fig. 12. The THD is calculated using fast Fourier transform (FFT) analysis technique. The electrical grid voltage THD is approximately 1.49% for the NPC topology.

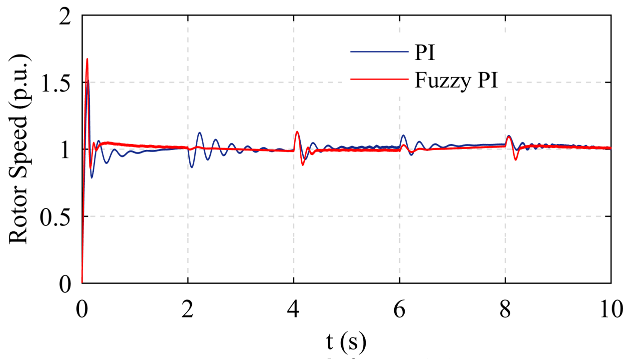



Fig.3. Rotor speed of PMSG (pu).

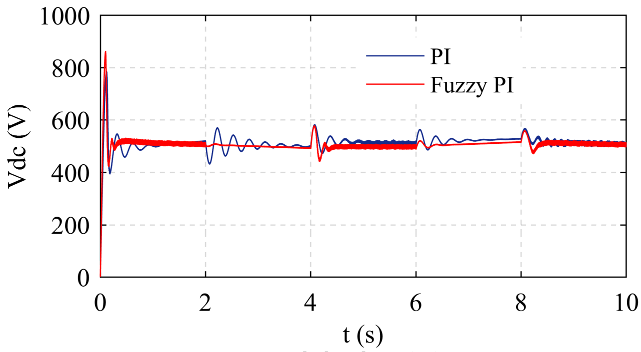



Fig.4. DC link voltage (pu)

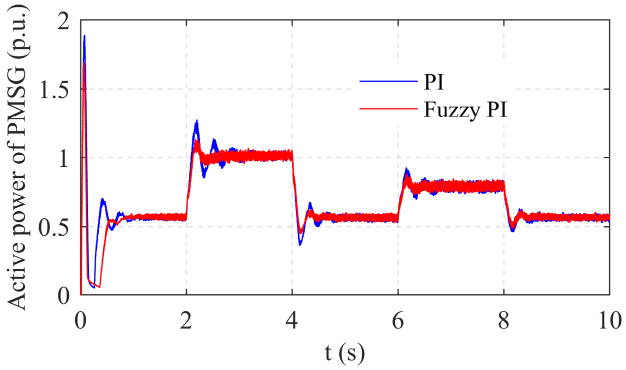



Fig.6. Active power of PMSG (pu)

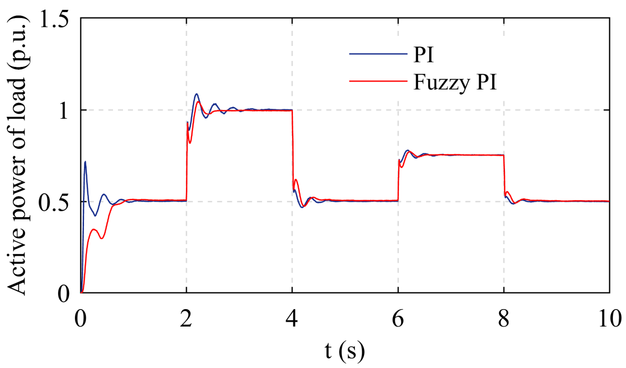



Fig.7. Active power of load (rms) (pu)

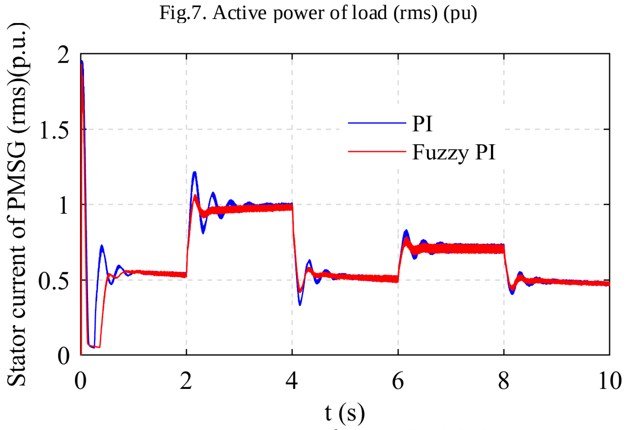



Fig.8. Stator current of PMSG (rms) (pu)

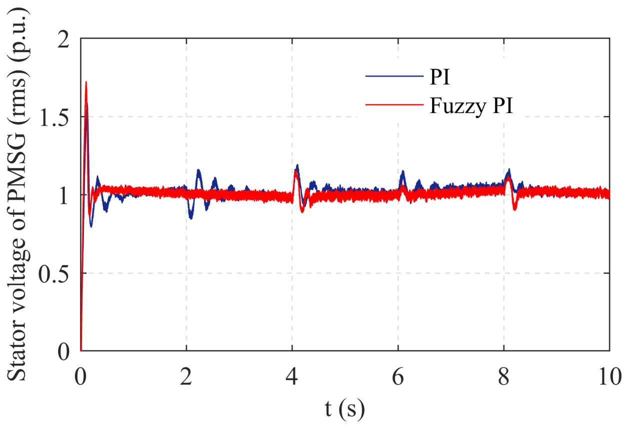



Fig.9. Stator voltage of PMSG (rms) (pu)

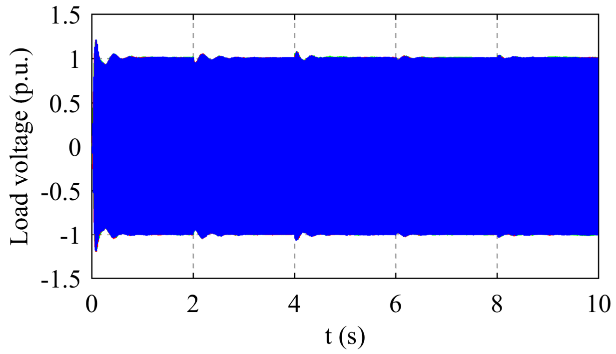



Fig.10. Load voltage (V)

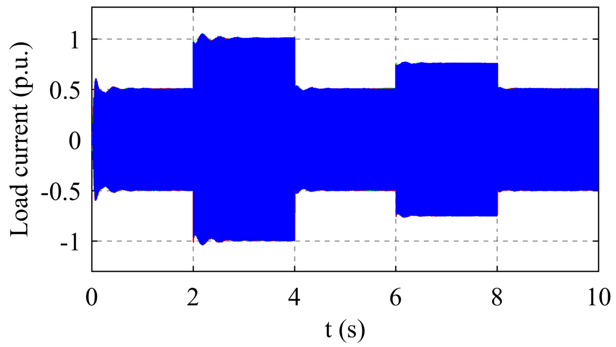



Fig.11. Load current (pu)

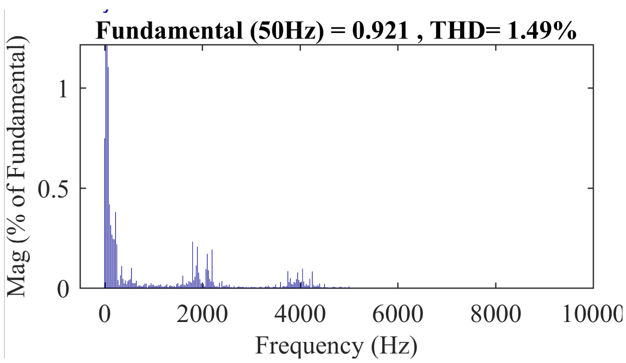



Fig.12. THD of injected voltage to grid.

## VI. Conclusion

The permanent magnet synchronous generator has been gained attention by wind turbine manufactures due to advance of control system and power electronics. A grid side converter and machine side converter for PMSG based on three level NPC using fuzzy PI is proposed in the study. Neutral point control system of the DC link can be implemented more easily than two level systems. From the Matlab/Simulink results, it is observed that the voltage balance of the DC link is controlled fairly well under the variation speed of the PMSG. The performance of the PMSG system under the effects of varying load condition is detailed investigated in this study. The performances of the PMSG using GSC and MSC based on three level NPC using fuzzy PI are analysed. The electrical grid voltage THD is approximately calculated 1.45% for the NPC topology. It is verified by performed analysis that the proposed model can be operated stably under varying load conditions.

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