Journal of Engg. Research Vol. 11 No(3A) pp.146-156 **DOI:10.36909/jer.15593**

Fuzzy gain Scheduled PID Controller for Power Quality Enhancement in Grid Connected Hybrid Solar PV-PEMFC Energy System

Mohamed Iqbal M [*], Altaf Badar[**], Pavithra C.V[*], Nithiyananthan K[***] and Mohamed Yousuff[****]

[*] *Department of Electrical and Electronics Engineering, PSG Institute of Technology and Applied Research, Coimbatore, Tamil Nadu, India*

[**] *Department of Electrical and Electronics Engineering, National Institute of Technology, Warangal, Telangana, India.*

[***] *Department of Electrical Engineering, King Abdulaziz University, Rabigh, KSA*

[****] *School of Computer Science and Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India*

Corresponding Author. Email: mohdiq.m@gmail.com.

Submitted : 09-09-2021

Revised : 22-11-2021

Accepted : 05-12-2021

ABSTRACT

Power quality improvement is inevitable due to the presence of power converters and non-linear loads in grid connected renewable based hybrid energy system (HES). The harmonics introduced by the distributed energy systems may lead to output voltage distortion and equipment failure which may lead to system losses. It may also cause for direct and indirect economic impacts. Development of active filter, passive filter and hybrid filter for harmonics mitigation would be an expensive solutions. Therefore, various DC/AC converter switching schemes are proposed for power quality improvements in grid connected Solar Photovoltaic (PV) and fuel cell based HES. Initially, Solar PV and Proton Exchange Membrane Fuel cell (PEMFC) are modeled using MATLAB/Simulink. Further the harmonic behavior with Proportional plus Integral (PI), Proportional plus Integral plus Derivative (PID) and Fuzzy gain scheduled PID controllers are demonstrated using Pulse Width Modulator (PWM). Converter output voltage waveform, frequency spectrum and total harmonics distortion (THD) values at the Point of Common Coupling (PCC) have witnessed that the fuzzy gain scheduled PID controller suppresses the voltage distortions completely. It also yields 4 percentage THD value which satisfies the harmonic level recommended by IEEE 519 standard. Comparative analysis shows that the fuzzy gain scheduled PID control scheme exhibits superior performance than the traditional PI and PID controllers. Therefore, it is identified as an effective control scheme for power quality improvement in hybrid renewable energy system.

Key words: Hybrid Energy System; Fuzzy Gain Scheduled PID Controller; Solar Photo-Voltaic; Proton Exchange Membrane Fuel Cell; DC/AC Converter Control; Total Harmonics Distortion

INTRODUCTION

Distributed energy sources such as solar, wind and fuel cell are an important alternative for improving the power system reliability under the prevailing energy crisis. It also helps to reduce CO2 emissions and minimize global warming issues (Shah et al., 2015). Solar photovoltaic (PV) system is highly preferred because of less operation and maintenance cost and cleanliness etc. But the intermittent nature of solar PV source requires suitable controllers maximum power generation and also for mitigation harmonics issues. Fuel cell source has also gained greater attention because of clean energy generation (Sun et al., 2018). The solar PV and fuel cell system will be the future competitor in renewable energy market from environmental perspective (Muhammad Tawalbeh et al., 2021). However, the rapid increase in power electronic converters and non-linear load usage causes power quality (PQ) issues which may also give rise to economic impacts and the poor equipment performance leading to system losses (Sharma et al., 2018; Sankar & Iqbal 2015). Therefore, the present work focuses on addressing PQ issues in grid-connected Hybrid Energy System (HES) comprising of solar PV and Proton Exchange Membrane Fuel Cell (PEMFC) system. Even though many attempts were made to overcome the effect of current harmonics by connecting the filter across the load, it has only very less applicability due to the probability of series and parallel resonance (Das 2004). Moreover the active filters also cannot help-out for the compensation as it require low-pass filter for average and oscillating parts of instantaneous power (Akagi 2005).

Further, a hybrid filter was also developed for the photovoltaic-fuel cell based system where the reactive power and harmonics compensation was performed by the combined effect of series active filter and shunt connected passive filter (Patra et al., 2015). It is also reported that the implementation of hybrid filters is more expensive for PQ improvement. In order to overcome all these limitations, an alternate way for solving the PQ issues by soft computing technique has been proposed in this work. For a varying load conditions, the controller needs to be adaptive with gain scheduling feature. Fuzzy logic technique has been proved as unique solution for grid connected operation (Mohamed Iqbal & Joseph Xavier 2014). In this paper, the fuzzy based intelligent self-tuning control scheme has been proposed for DC/AC converter control for a HES and its total harmonics distortion (THD) level is compared with that of conventional PI and PID controller. Since, the fuzzy gain scheduling PID controller satisfies the IEEE 519 standard for harmonics limit (Halpin 2003), it is identified as an effective control scheme for harmonic mitigation in grid connected hybrid solar PV-PEMFC energy system.

MODELING OF HYBRID ENERGY SYSTEM

Electrical power industries have moved to cleaner energy generation modes such as solar, wind, fuel cell etc. due to environmental constraints and new energy policies (Naidu & Meikandasivam 2020). This paper presents the modeling and control of grid connected HES comprising Solar PV and PEMFC. Even though the solar PV is the matured source of energy and economically viable technique for power generation, it suffers from voltage fluctuations due to irregular temperature and irradiation (Mahiraj & Shelly 2019). Therefore, an appropriate modeling of the system and harmonic mitigation are essential for ensuring reliable operation. The solar cell has been modelled based on the most influencing parameters viz., irradiation (G), temperature (T) and load condition as shown in Equation (1). The photo voltaic current, I_{PV} and diode saturation current I_D are expressed as shown in Equation (2) and Equation (3).

$$I = I_{PV} - I_D\left[e^{\frac{q(V+IR_S)}{\alpha kT}} - 1\right] - \left[\frac{V+IR_S}{R_P}\right] \tag{1}$$

$$I_{PV} = \frac{G}{G_{Ref}}(I_{SC} + K_S * \Delta T) \tag{2}$$

$$I_D = I_{rs} * \left(\frac{T_{OP}}{T_{Ref}}\right)^3 * exp\left[\frac{qE_g}{\alpha k}\left(\frac{1}{T_{OP}} - \frac{1}{T_{Ref}}\right)\right] \tag{3}$$

PEMFC is one kind of fuel cells that can work with comparatively high efficiency and zero emission (Wee 2007). It has gained unique merits like low operating temperature, less weight, compactness, long stack life, sustained operation at a high current density, etc. (Doumbia 2014). PEMFC requires hydrogen and oxygen as reactants and an ion-conductive membrane coated with platinum as active catalyst. The operating temperature of PEMFC lies between 70 and 100$^{\circ}C$. Equation (4) gives the relationship between partial pressure (P_{H_2}) inside the channel and molar flow of hydrogen gas (q_{H_2}).

$$\frac{qH_2}{PH_2} = \frac{K_{an}}{\sqrt{MH_2}} \tag{4}$$

Molar flow of hydrogen gas can be evaluated using Equation (5) based on three factors namely hydrogen input flow ($q_{H_2}^{INPUT}$), flow during reaction ($q_{H_2}^{REACTION}$) and output flow ($q_{H_2}^{OUTPUT}$). Flow rate of reacted hydrogen is expressed in Equation (6). The partial pressure of hydrogen is found using Equations (4) to (6) and given in Equation (7).

$$\frac{dPH_2}{dx} = \frac{RT}{V_{an}}\left(qH_2^{INPUT} - qH_2^{OUPUT} - qH_2^{REACTION}\right) \tag{5}$$

$$qH_2^{REACTION} = \frac{N_O I_{FC}}{2F} = 2K_r I_{FC} \tag{6}$$

$$PH_2 = \frac{{}^{1}/_{KH_2}}{1+\Gamma H_2 S\left(qH_2^{INPUT} - 2K_r I_{FC}\right)} \tag{7}$$

Where, $\Gamma H_2 = \frac{V_{an}}{RTKH_2}$

In a similar way, partial pressure of oxygen (P_{O_2}) and water (P_{H_2O}) can also be found. Assuming constant oxygen concentration and temperature, the Nernst instantaneous DC output voltage (E) of PEMFC is expressed in Equation (8). On the basis of mathematical modelling of a fuel cell, a MATLAB/Simulink model for PEMFC with flow rate regulator is obtained using the model parameters as shown in Table 1.

$$E = N_O\left[E_O + \frac{RT}{2F} log\left[\frac{PH_2\sqrt{PO_2}}{PH_2O}\right]\right] \tag{8}$$

Figure 1, presents a MATLAB/Simulink model of the proposed HES with solar PV and PEMFC. During normal condition, d-axis voltage would be '1' pu and q-axis voltage would be zero. After 'dq0' transformation, the 'dq' voltages are compared with their normal reference values. This error signal can be controlled and regulated by the controller and converted back to 'abc' components. For the synchronization of frequency and phase, the discrete Phase Locked Loop is used (Chung 2000). Control of DC/AC converter for PQ enhancement is presented in next section.

Table 1 Model parameters for PEMFC

Model parameters	**Value**
Stack Power	6kW
Fuel cell resistance (*Ω*)	0.07833 *Ω*
Voltage of single cell (V)	1.1288V
Number of cells	65
Nominal stack efficiency (%)	55
Stack voltage (V)	45V

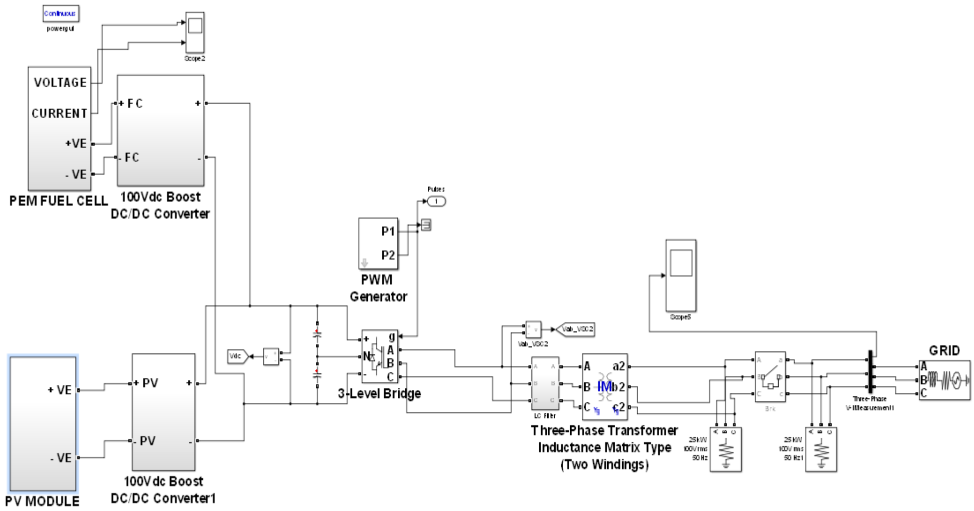

Figure 1 MATLAB/Simulink model of proposed Hybrid Energy System

POWER QUALITY IMPROVEMENT

Renewable Energy capacity addition in electricity grid also demand for usage of PQ compensators (Wang 2012). Power converters which became a part of electricity grid causes an undesirable effects on PQ and power system reliability (Deepika et al., 2017). Harmonic mitigation can be achieved by means of adopting suitable switching methods for DC/AC converter (Dahidah & Agelidis 2008). PI and PID controllers can be used for the converter control because of its simplicity and high reliability (Kuo 1995). Fuzzy logic based controllers are relatively cheaper and simpler to implement with less computational burden (Daud et al., 2017). Therefore, Fuzzy tuned PID controller has been proposed in this paper for the control of DC/AC converter and its effectiveness with PI and PID controllers are analysed.

PI and PID Control of DC/AC Converter

Initially, Proportional Integral (PI) controller is implemented with the HES for controlling the switching frequency of IGBT. Proportional gain, Kp and integral gain, Ki in the proposed HES are tuned by the classical tuning rules of Ziegler–Nichols method (Ziegler & Nichols 1942). The PI controller controls the external signal of PWM generator and hence decides the switching frequency of the converter. Similarly, Proportional gain (Kp), integral gain (Ki) and derivative gain (K_d) of PID controller are tuned by the classical tuning rule of ZN method (Mohamed Iqbal et al., 2014). The control output signal of PI and PID controllers as a function of voltage error signal, $e(t)$ are expressed in Equation (9) and (10) respectively.

$$C_{PI}(t) = K_P e(t) + K_i \int e(t)dt \tag{9}$$

$$C_{PID}(t) = \left[K_P e(t) + K_i \int e(t)dt + K_D \frac{de(t)}{dt}\right] \tag{10}$$

The controllers are implemented in MATLAB/Simulink model and the output voltage waveform and frequency spectrum are obtained by simulating up to 50 ms.

Fuzzy Gain Scheduled PID Control of DC/AC Converter

Fuzzy gain scheduled PID controller is an effective approach for applying fuzzy rules and its reasoning ability for self-tuning the gains (Ramirez-Ganzalez & Malik 2010). It is also evident that the Fuzzy-PID controllers result in smoother controller output when compared to the conventional PI and PID controllers (Mohamed Iqbal et al., 2014). In this paper, Fuzzy-PID controller is developed using Sugeno fuzzy inference model as it is found as an efficient gain scheduler (MATLAB 2000). The control structure of fuzzy gain scheduled PID controller for DC/AC converter is shown in Figure 2.

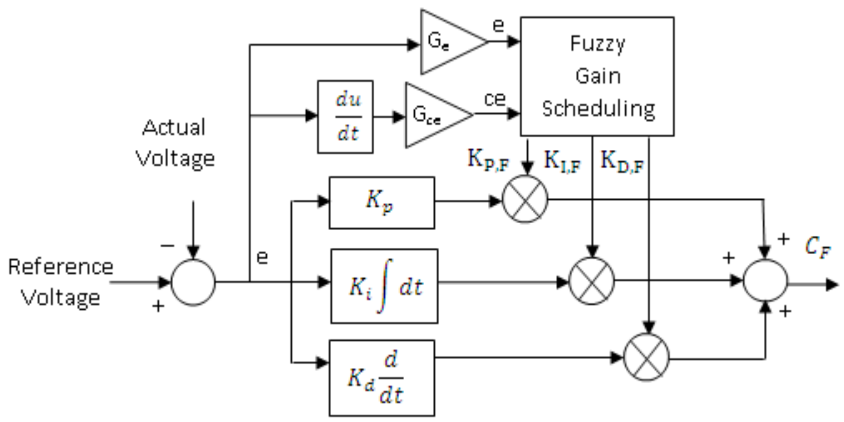

Figure 2 Fuzzy logic tuned PID controller for DC/AC converter control

Input signals are error (e) and derivative of error (ce) of voltage signal and the fuzzy tuned gains viz., K_{PF}, K_{IF}, K_{DF} are the output signals. Triangular membership function and constant membership function are used for input and output signals as shown in Figures 3 and 4 respectively. Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB) are the variables chosen for input signals. However, seven fuzzy sets, namely Very Big (VB), Medium Big (MB), Big (B), Medium (M), Medium Small (MS), Small (S) and Zero (Z) have been selected for output signals. Based on the expert knowledge, Fuzzy IF-THEN rules are framed for the gains K_{PF}, K_{IF} and K_{DF} as shown in Table 2.

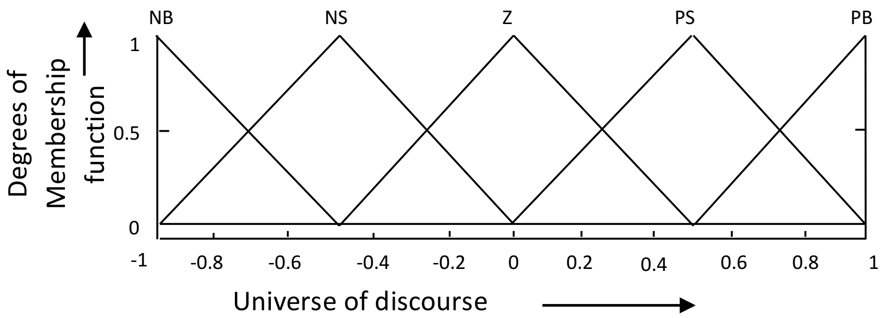

Figure 3 Input membership function for Fuzzy-PID controller

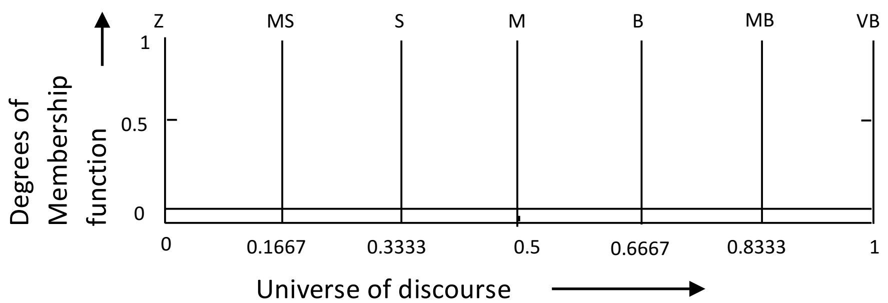

Figure 4 Output membership function for Fuzzy-PID controller

Table 2 Fuzzy rule base for K_{PF}, K_{IF} and K_{DF}

e	Ce														
	PB			PS			Z			NS			NB		
NS	VB	S	VB	MB	S	VB	B	S	MB	B	S	B	B	S	Z
NB	VB	M	VB	VB	M	MB	VB	M	M	VB	M	S	VB	M	Z
PB	VB	M	VB	VB	MS	VB	VB	M	VB	VB	M	VB	VB	M	VB
PS	VB	S	VB	MB	S	VB	B	S	VB	B	S	VB	B	S	B
Z	S	MS	VB	S	MS	VB	MS	Z	MB	Z	MS	MB	Z	MS	M
NS	VB	S	VB	MB	S	VB	B	S	MB	B	S	B	B	S	Z
NB	VB	M	VB	VB	M	MB	VB	M	M	VB	M	S	VB	M	Z

Further, the self-tuning PID gains K_{PS},K_{IS}, K_{DS} are found through the product of output and conventional PID gains. The output control signal using the fuzzy PID controller is expressed by Equation (11).

$$C_F(t) = K_{PS}e(t) + K_{IS}\int e(t)dt + K_{DS}\frac{de(t)}{dt} \tag{11}$$

Self-tuned PID controller gains for the proposed HES are tuned by using the above procedure and simulation responses are analyzed to identify the effective control technique.

RESULTS AND DISCUSSION

The control schemes presented in previous sections are implemented in MATLAB/Simulink model of the proposed Solar PV and PEMFC hybrid system. The output voltage from both the sources are given to a common DC bus. DC/AC converter output voltage and its harmonics level are controlled by the PWM generator. It is necessary to satisfy the harmonics level recommended by IEEE 519 standard (Halpin 2003). In this paper, Fast Fourier Transform (FFT) analysis is used for evaluating THD values of the proposed hybrid system. The output voltage waveform of grid connected HES and its frequency spectrum have been obtained by simulating the MATLAB/Simulink model up to 50 ms. Figures 5 and 6 show output voltage waveform along with the frequency spectrum before implementing the controllers. It is witnessed from the voltage response that the voltage distortions are more at Point of Common Coupling (PCC). Total Harmonic Distortion (THD) value is also found to be 27.60 percentage which is not within the acceptable harmonic limit.

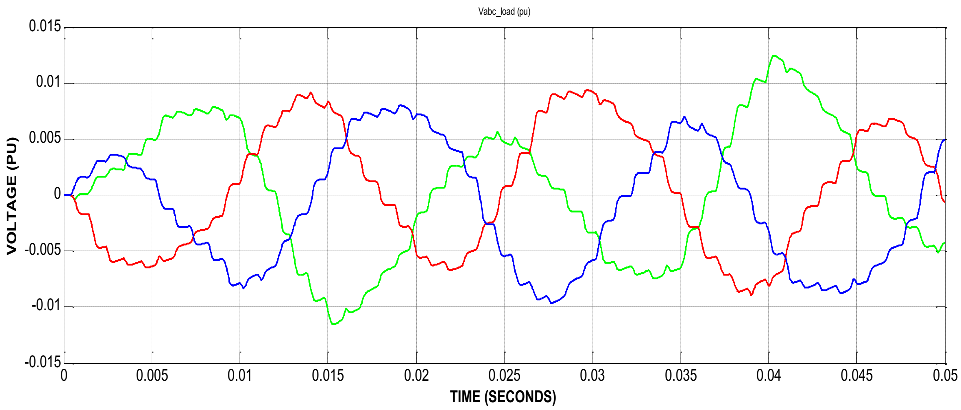

Figure 5 Output voltage waveform without controller

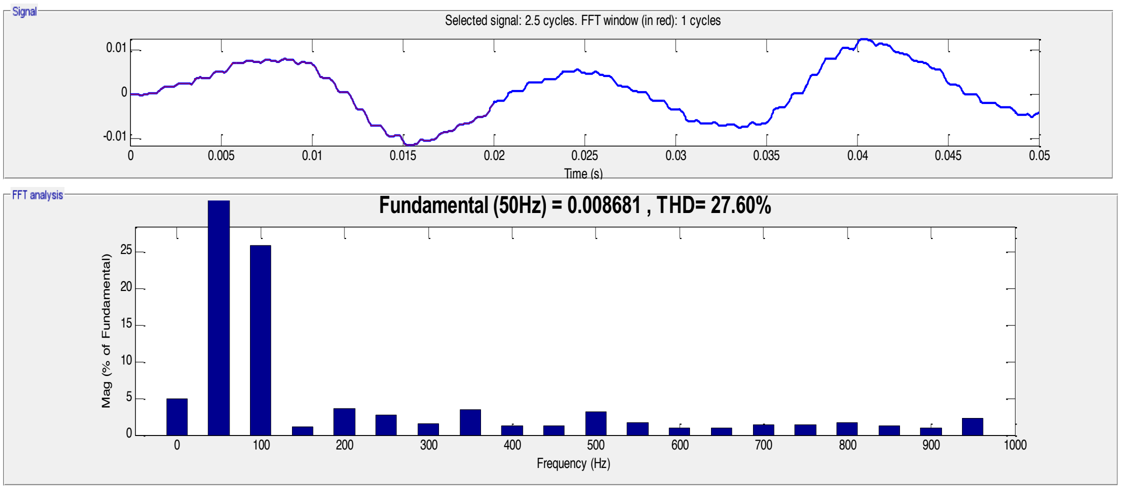

Figure 6 Frequency spectrum of output voltage without controller

In order to mitigate the harmonics various control techniques namely PI, PID and Fuzzy-PID controllers are implemented with the proposed system and the output voltage waveforms are obtained as shown in Figures 7, 8 and 9 respectively. It is witnessed that PI and PID controllers helps to reduce the voltage distortions. However the Fuzzy gain scheduled PID controller has suppressed the voltage distortions satisfactorily.

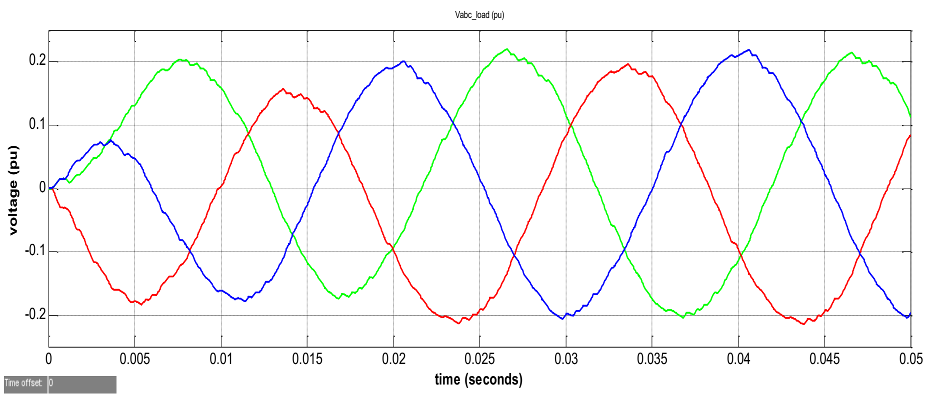

Figure 7 Output voltage waveform with PI controller

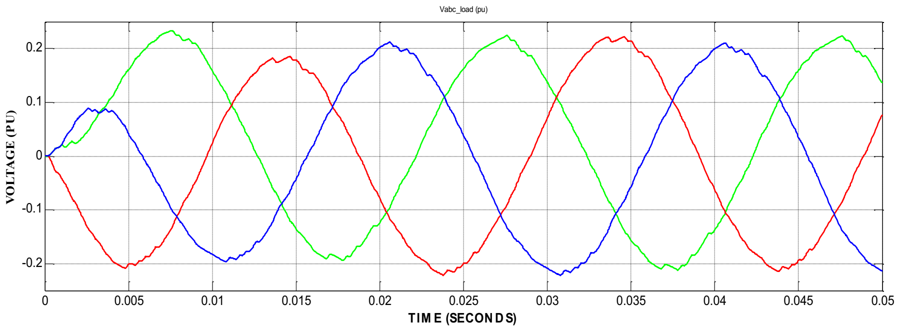

Figure 8 Output voltage waveform with PID controller

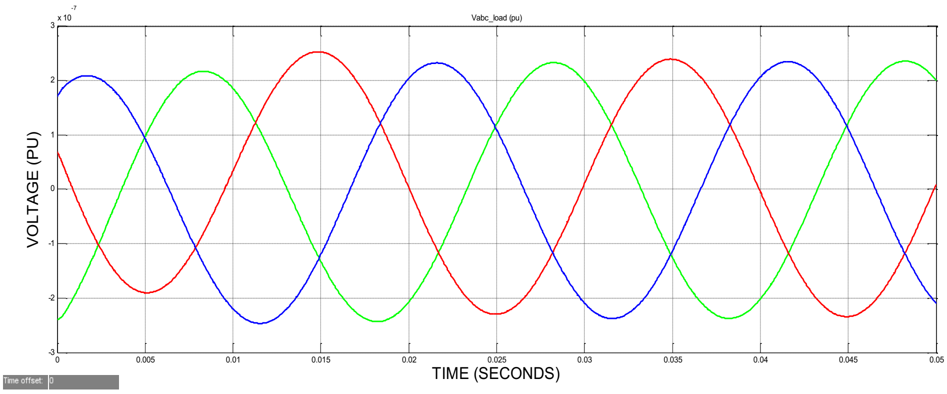

Figure 9 Output voltage waveform with Fuzzy-PID controller

The frequency spectrum of the HES with PI, PID, Fuzzy-PID control schemes are also obtained for analysis and presented in Figure 10, 11 and 12 respectively. It has been found that the PI controller reduces the THD value from 27.60 percentage to 19.05 percentage. Further the PID controller yield the THD value of 17.0 percentage which is an improved response than PI controller as given in Table 3. But the response does not satisfy the IEEE recommended limit for harmonics.

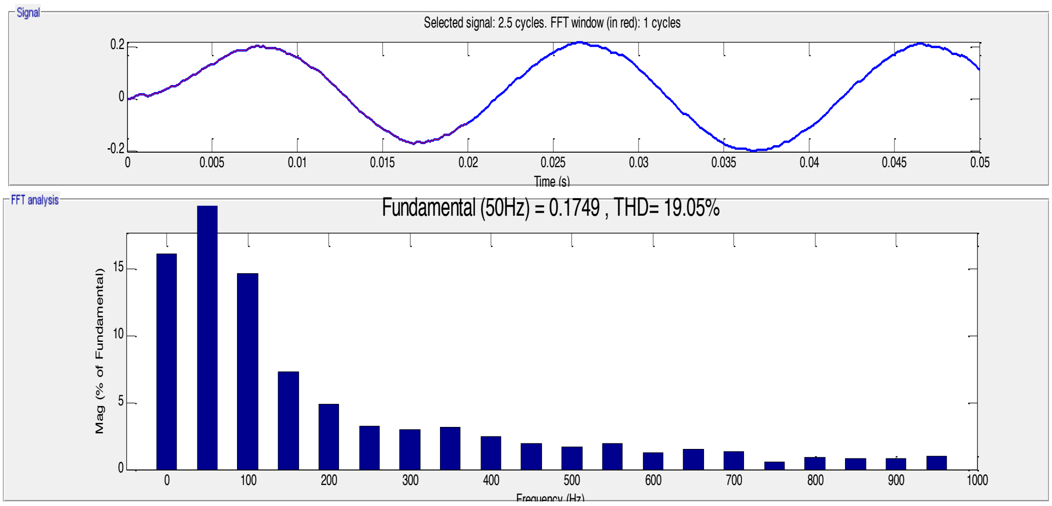

Figure 10 Frequency spectrum of output voltage with PI controller

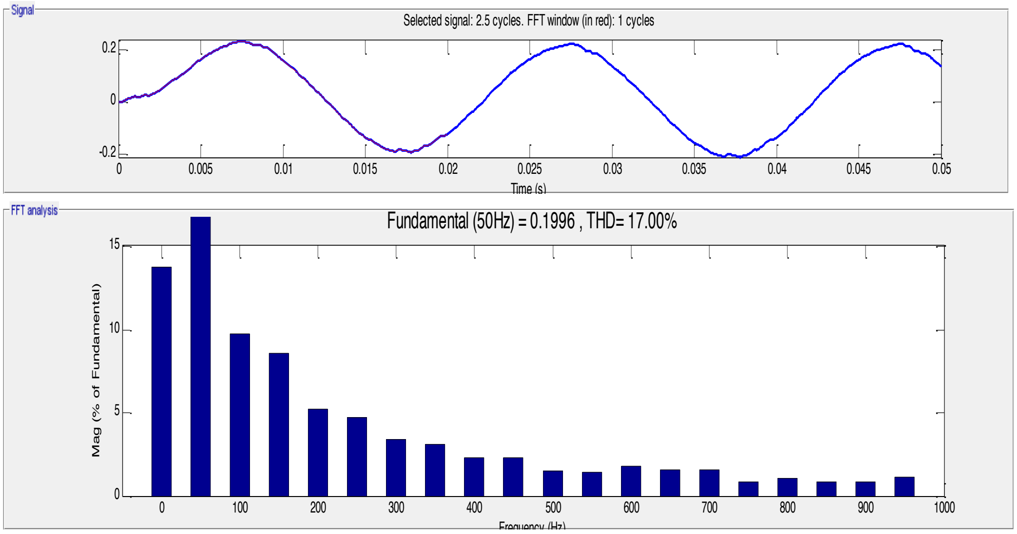

Figure 11 Frequency spectrum of output voltage with PID controller

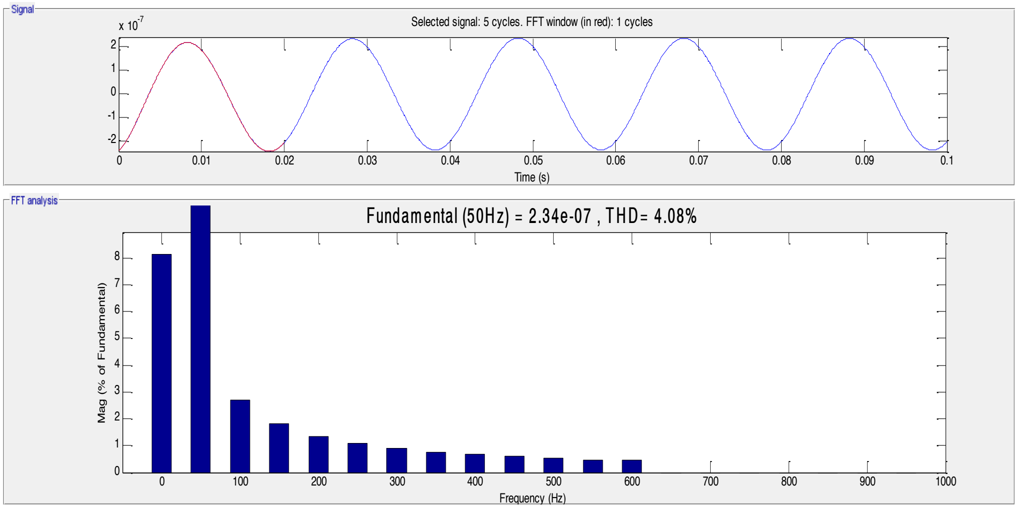

Figure 12 Frequency spectrum of output voltage with Fuzzy-PID controller

Table 3 THD values for various control schemes

Controller scheme	Total Harmonic Distortion (THD) (%)
Without Controller	27.60
PI Controller	19.05
PID Controller	17.00
Fuzzy PID Controller	4.08

As per IEEE standard 519, the THD value should be maintained less than 5 percentage (Halpin 2003). On comparing the simulation results of all control schemes, Fuzzy-PID controller has drastically improved the harmonic level as the THD value is below 5 percentage. Therefore the Fuzzy-PID controller has been identified as an effective control technique for the PQ enhancement of Solar PV-PEMFC hybrid energy system in grid connected operation. The proposed self-tuning approach for DC/AC converter is also cost effective solution than using the expensive hybrid filters for PQ enhancement (Patra et al., 2015). Further, the proposed fuzzy PID control technique is very much adaptive to disturbances and hence can be implemented to any dynamic system using FPGA or Microcontroller based implementation.

CONCLUSION

A novel control strategy for mitigating the harmonics of grid interactive Solar PV-PEMFC hybrid energy system has been proposed as a replacement for the filter based compensation. PI, PID and Fuzzy tuned PID controllers are implemented for regulating the PWM pulse generator which is responsible for harmonic mitigation. Output voltage waveform and frequency spectrum of the PI and PID controller reveals that the voltage distortions are reduced by PI and PID controllers and the harmonic levels are 19.5 and 17.0 percentage respectively, which are above the IEEE recommended limit. Moreover these control schemes are not adaptive as the controller gains are fixed values tuned by conventional ZN method. Hence PI and PID control of DC/AC converter would not help to reduce the harmonics. Further, adaptive and self-tuned fuzzy PID control scheme proposed in this paper is very much effective to achieve distortion-less and pure sinusoidal voltage for HES. THD value is also drastically reduced to 4 percentage which satisfies the harmonic limit recommended by the IEEE 519 standard (< 5 percentage). Since the fuzzy self-tuning control scheme is based on the ‘expert knowledge base’ and the ‘IF-THEN fuzzy rules’, it can be applied for PQ improvement in any real time system using state-of-art microcontroller or FPGA based implementation. Based on the PQ characteristics, adaptive nature and applicability of fuzzy tuned PID controller to any dynamic system, Fuzzy gain scheduled PID controller is identified as effective control scheme for PQ enhancement of Solar PV-PEMFC hybrid energy system.

REFERENCES

Shah, R.; Mithulananthan, N.; Bansal, R. C.; Ramachandaramurthy, V. K. 2015. A review of key power system stability challenges for large-scale PV integration. Renewable and Sustainable Energy Reviews. 41: 1423-1436.

Sun, L.; Wu, G.; Xue, Y.; Shen, J.; Li, D.; Lee, K.Y. 2018. Coordinated Control Strategies for Fuel Cell Power Plant in a Microgrid. IEEE Transactions on Energy Conversion. 33(1): 1-9.

Muhammad Tawalbeh, Amani Al-Othman, Feras Kafiah, Emad Abdelsalam, Fares Almomani, Malek Alkasrawi. 2021. Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook, Science of The Total Environment. 759.

Sharmaa, A.; Rajpurohita, B.S.; Singh, S.N. 2018. A review on economics of power quality: Impact, assessment and mitigation. Renewable and Sustainable Energy Reviews. 88: 363-372.

Sankar, S. L. & Iqbal, M. M. 2015. ANSI and IEC Standards Based Short Circuit Analysis of a Typical 2× 30 MW Thermal Power Plant. Middle-East Journal of Scientific Research. 1617-1625.

Das, J. C. 2004. Passive filters-potentialities and limitations. IEEE Trans. Ind. Appl. 40(1): 232–241.

Akagi, H. 2005. Active harmonic filters. Proc. IEEE. 93(12): 2128–2141.

Patra, S.; Ankur.; Narayana. M.; Mohanty, S. R.; Kishor, N. 2015. Power quality improvement in grid-connected photovoltaic–fuel cell based hybrid system using robust maximum power point tracking controller. Electric Power Components and Systems. 43(20): 2235-2250.

Mohamed Iqbal, M.; Joseph Xavier, R. 2014. Fuzzy Self Tuning PID Controller for Speedtronic Governor Controlled Heavy Duty Gas Turbine Power Plants. Electric Power Components and Systems. 42 (14): 1485-1494.

Halpin, M. 2003. Overview of revisions to IEEE standard 519-1992. In CIGRE/IEEE PES International Symposium Quality and Security of Electric Power Delivery Systems. CIGRE/PES 2003. 65-68.

Naidu, R. P. K.; Meikandasivam, S. 2020. Power quality enhancement in a grid-connected hybrid system with coordinated PQ theory & fractional order PID controller in DPFC. Sustainable Energy, Grids and Networks. 21: 100317.

Mahiraj, S. R.; Shelly, V. 2019. A Comprehensive Review on Impact of Wind and Solar Photovoltaic Energy Sources on Voltage Stability of Power Grid. Journal of Engineering Research. 7 (4): 178-202.

Wee, J. H. 2007. Applications of proton exchange membrane fuel cell systems. Renewable and sustainable energy reviews. 11 (8): 1720-1738.

Doumbia, M. L. 2014. PEM Fuel Cell Modelling Using Artificial Neural Networks. International Journal of Renewable Energy Research. 4 (3): 725-730.

Chung, S. K. 2000. Phase-locked loop for grid-connected three-phase power conversion systems. IEE Proceedings on Electric Power Applications. 147 (3): 213-219.

Wang X.; Guerrero JM.; Blaabjerg F.; Chen Z. 2012. A review of power electronics based microgrids. Journal of Power Electronics. 12: 181-192.

Deepika, G.; Elakkiya, M.; Mohamed Iqbal, M. 2017. Harmonics reduction using multilevel based shunt active filter with SMES. Int J Eng Technology. 9(2): 1001-1011.

Dahidah MSA.; Agelidis VG. 2008. Selective Harmonic Elimination PWM Control for Cascaded Multilevel Voltage Source Converters: A Generalized Formula. IEEE Transactions on Power Electronics. 23: 1620-1630.

Kuo, B. C. 1995. Automatic Control Systems, 7th ed., Prentice Hall.

Daud, W. R. W.; Rosli, R. E.; Majlan, E. H.; Hamid, S. A. A.; Mohamed, R.; Husaini, T. 2017. PEM fuel cell system control. A review Renewable Energy. 113: 620-638.

Ziegler, J. G.; Nichols, N. B. 1942. Optimum settings for automatic controllers. ASME Trans. 64 (11).

Ramirez-Ganzalez, M.; Malik, O. P. 2010. Self-tuned power system stabilizer based on a simple fuzzy logic controller. Elect. Power Compon. Syst. 38 (4): 407–423.

MATLAB. 2000. Optimization Toolbox. Mathworks Inc.

Martins, F. G. 2005. Tuning of PID controllers using the ITAE criterion. Int. J. Eng. Ed. 21 (5): 867–873.