Control technique for power quality improvement of isolated wind power generation system

Goksu Gorel[1], Inas Fadhil[2]
[1]Department of Electrical and Electronics Engineering, Çankırı Karatekin University, Çankırı, Turkey
[2]Department of Electronic, Institute of Technology/Baghdad, Middle Technical University, Baghdad, Iraq

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ABSTRACT

Power quality (PQ) problems for renewable energy system (RES) is major challenge for using these systems. Amplitude, frequency, and waveform is important PQ parameters especially for standalone or isolated systems. In this paper we propose RES with wind turbine (WT) and permanent magnet synchronous generator (PMSG) to feed different loads (liner, non-liner) through AC-DC-AC converter. The PMSG operate with fuzzy logic inertia controller, to convert turbine torque form PU to Nm. The inverter stage in the converter operate according to proportional integral derivative (PID) controller with 3rd harmonic injection pulse width modulation (PWM) to regulate the AC voltage in load side. For the same case study and operating condition, we compared the result for system parameters when using ordinary PWM and using PID with 3rd harmonic injection. Voltages total harmonics distortion (THD) was less than 2% with liner loads, and 3.5% with non-liner load and the same was for current load, the voltage amplitude was between (1-1.03) PU under different wind speed by using the proposed controller.

Corresponding Author:

Goksu Gorel
Department of Electrical and Electronics Engineering, Çankırı Karatekin University
Uluyazi Campus, G Building, Floor 2, Merkez, Cankiri, Turkey
Email: goksugorel@karatekin.edu.tr

1. INTRODUCTION

In the recent years there was a transition toward using renewable energy for lowering emission, and power losses in the transmission lines. Photovoltaic panels (PV) and wind turbine (WT) are considered the most known forms of renewable energy system (RES) applications. The intermittent nature for RES is the major drawback for these systems. Speed control for WT is very critical point in power generation, which is affected by the method of connecting the generator with loads or grid, such as full converter with generator, wound rotor generator equipped with resistance, or double feed induction generator (DFIG), and operate with fixed speed. According to Gajowik *et al.* [1], AC-DC-AC converter consists of back to back with break chopper has been used for grid connected WT with 10 kW variable speed asynchronous generator with 700 V DC-link, and the maximum power losses were 420 W. Also, AC-DC-AC converter can be used with maximum power tracking for optimal power extraction and improving WT performance under fluctuating wind speed and provides good dynamic performance [2]. Power fluctuations is not related only to DFIG but also permanent magnet synchronous generator (PMSG), phase-locked loop (PLL) control technic was applied on PMSG side converter for damping power oscillations and maximum power point tracking [3]. According to, Jaiswal *et al.* [4] fuzzy logic controller in the turbine side and PI controller on the load side were applied on 1,050 V DC link converter connected with PMSG, the proposed control structure aimed to improve power quality (PQ) for PMSG and maximum power point tracking (MPPT). Hysteresis current control technic was used with AC-DC inverter in [5] for WT, this technic need peak and valley current detectors which were compromised of RC integrator and RS flip flop to detect the values in real time, the generator in this work was 2 KVA, 1,800 rpm speed and doesn't need slip rings and brushes, it's also maintenances free without rare earth magnets. Nguyen *et al.* [6] presents review grid forming inverter with WT generators controllers with single or multi loop, and provides comparison for different structures of applying current and voltage control schemes. In addition, the challenges of applying these growing functional modules (GFM) controls to WTs, including the impact of DC-link voltage and the current saturation algorithm on the GFM control performance. Using controlled AC-DC-AC converter can give full control to active and reactive power injection or consumption between utility grid and WT, also PQ especially total harmonics distortion (THD) and efficiency are affected by inverter structure and switching technic, the proposed structure in this work consists of two 1.5 kW machines, a DC motor which acts like static-dynamic behaviors of a three-blade WT with a horizontal axis, and a synchronous generator that ensures the electromechanical conversion and manages the different operating modes [7]. The aim of the first part in this work is the design and the implementation of the control of the grid side converter in order to control the flow of active and reactive power in both directions between the generator and the grid. According to Majout *et al.* [8] sliding mode control was compared with conventional control technics for pulse width modulation (PWM) of load side and PMSG side converters, current THD was 3.05% for the conventual technic, and 1.25% for slide mode control (SMC). The structure of stand-alone may vary from system to another according to generator type or rated power. Also, the converter type changes according to the system structure, propose two common converters for PMSG, the first is back-to-back power converter, the second is a three-phase diode rectifier with unregulated DC-link, and a boost converter [9]. The second structure can be used with isolated and grid connected systems. G-Torres *et al.* [10] a novel control strategy applied on back-to-back converter with DC-link connected with PMSG for MPPT and improve PQ profile. APF was used to improve PQ for isolated WT with PMSG feeding non-liner load and compare the results with tuning inductors and capacitors (LC) filter, the proposed active power filter has been observed to be capable of minimizing the source current harmonics without requiring fine tuning of components, keeping the power factor near unity over a wide variation of load [11]. According to Poudel *et al.* [12] a comparative study for control methods in isolated hybrid power systems was proposed, voltage fluctuations and frequency oscillations requires robust control strategies which can be achieved by choosing the proper soft computing algorithm such as genetic algorithm (GA), particle swarm (PS), mine blast algorithm, and other applications of artificial intelligence (AI). In this paper we are going to use isolated PMSG with WT to feed loads with different power factor and non-liner load, the total load will be varied during simulation time, in beginning the wind speed is fixed then the wind speed will be variable. Fuzzy logic inertia controller will be used to calculate mechanical torque for PMSG, also close loop controller for the inverter stage was used to regulate output voltage amplitude during the changes in wind speed and loads, finally LC filter at inverter stage's output to mitigate harmonics.

2. STRUCTURE OF ISOLATED WINDTUBINE WITH PMSG

The small scale stand-alone in this paper consists of 10 kW PMSG, connected with WT. This installation is feeding loads with different natures such as resistive, combined, and non-liner load, through AC-DC-AC converter. There are many parameters to indicate PQ especially voltage, such as amplitude, and THD [13]. The proposed system will use rectifying stage at the output of PMSG to convert the AC to DC voltage, after that it will be converted by PWM controlled inverter stage with 3rd harmonics injection, to regulate the voltage in the load side with minimum THD. Figure 1 shows the proposed stand-alone system.

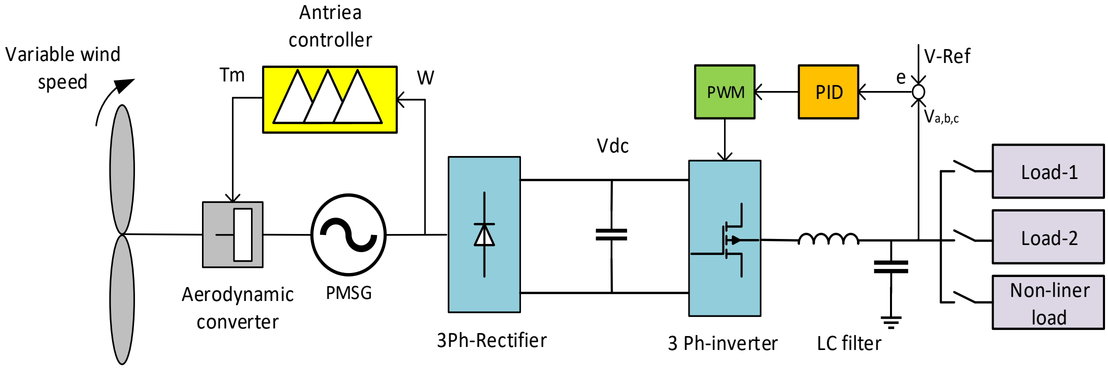

Figure 1. The proposed WT with converter installation

2.1. Wind turbine with PMSG

PMSG is usually used with small scale WT s [14], this installation has two main parts, the first part is the WT which transport the mechanical power of the wind to the PMSG. The kinetic energy of an object is given by:

$$E = \frac{1}{2}.m.v^2 \tag{1}$$

Where: v is velocity, m is Mass, the power can be defined as:

$$P = \frac{1}{2}.\rho.v^3.A \tag{2}$$

Not all the wind power will be converted to mechanical power, according to Betz low there's coefficient factor Cp for the WT determine the amount of extracted power from the wind which can be given by:

$$C_p = \frac{P_o}{P} \tag{3}$$

the power converted from the wind speed Po is:

$$P_O = C_p\,\frac{1}{2}.\rho.A.v_1^3 \tag{4}$$

The second part is the PMSG with the characteristics as illustrated in Table 1. Figure 2 show this simulation for WT with PMSG. Inertia controller use fuzzy logic to convert the mechanical torque from PU to Nm and adjust its value to regulate the electrical output power for the PMSG especially in starting stage, also to regulate the DC voltage to operate the generator with unity power factor.

Table 1. PMSG parameters

Rated power	10 kVA
Number of pair pole	2
Nominal rotator speed	1,500 RPM
Stator phase resistance Rs	0.0485 Ω

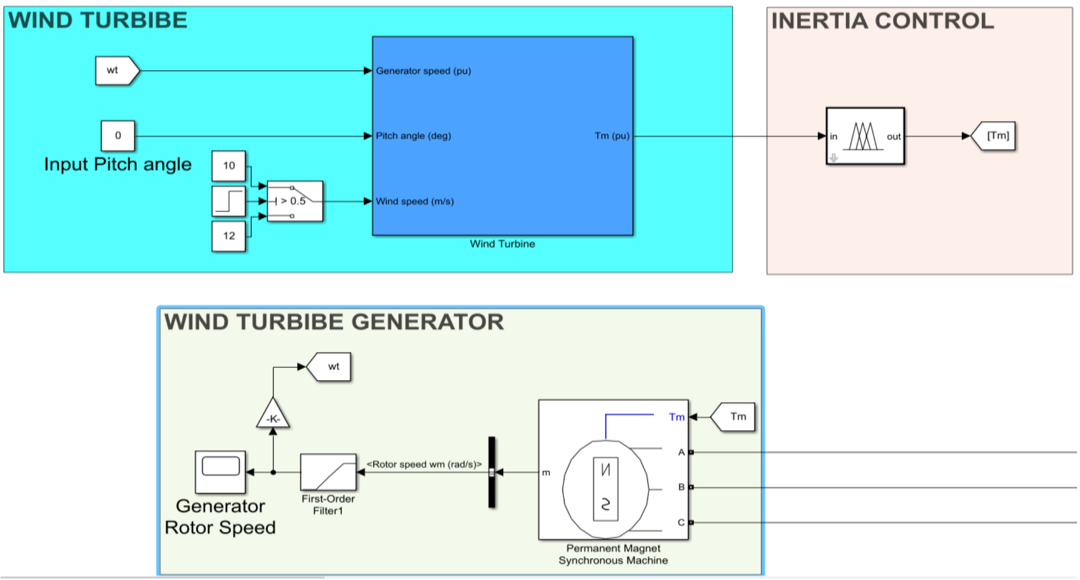

Figure 2. WT with PMSG simulation in MATLAB/Simulink

2.2. DC-AC converter

This component consists of three phase diode rectifiers [15] and half bridge three phase inverter with MOSFET switches, Figure 3 shows the proposed structure for AC-DC inverter. The AC inverter stage is will be controlled by proportional integral derivative (PID) controller which will regulate the module signal in sensual pulse width modulation (SPWM), also 3rd harmonics injection will be used to mitigate THD. SPWM is pulsing technic where it compares sine wave (modeled signal) with sawtooth wave (carrier signal) and generate pulses for the switches [16], [17]. The main idea of 3rd harmonics injection is to add another sine wave with modeled wave so the 3rd harmonic will be eliminated in the output voltage for the inverter. Figure 4 shows the concept for the proposed inverter stage controller. Modeled wave amplitude also can affect the output voltage amplitude, with using PID controller we can adjust modeled wave amplitude by comparing the output voltage RPM in PU with reference voltage [18]. Figure 5 shows the proposed structure for inverter stage controller.

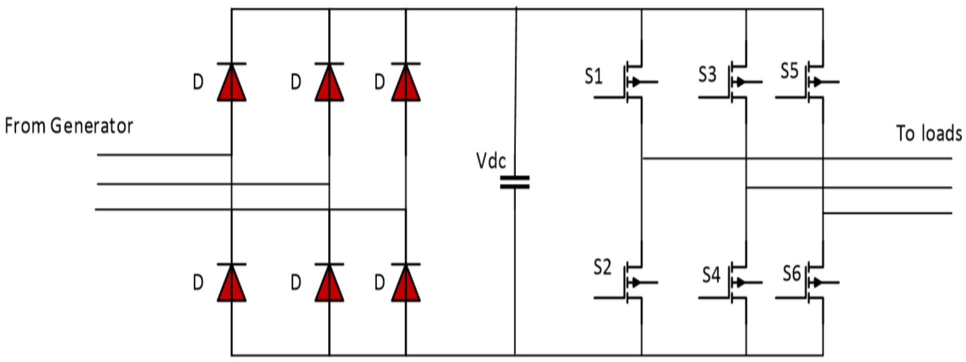

Figure 3. The proposed structure for AC-DC inverter

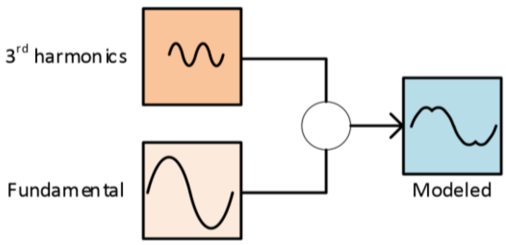

Figure 4. 3rd harmonic injection principle

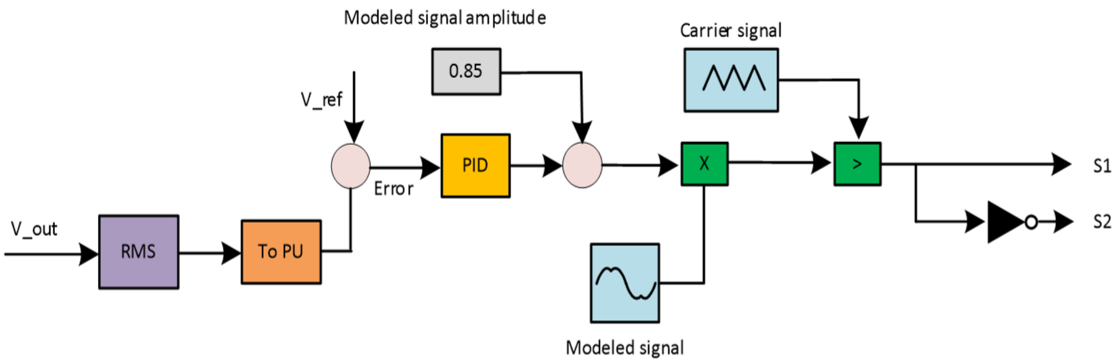

Figure 5. Inverter side full controller structure

The RES is off grid which requires adjusting voltage amplitude regardless the changes in the load side, and in generating side. Using this structure for pulse generating technics grantee this need. Also using 3rd harmonics injection will lower THD in voltage and current waves. After applying PI on the error, the controller will adjust the amplitude of the modeled signal which will be compared with carrier signal to generate pulses for the switches. PI controller output is the results for two parameters Kp the proportional constant, and Ki the integrator constant as the following (5) [19]:

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (5)$$

by taking Laplace for the pervious equation:

$$G(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} \quad (6)$$

2.3. Electrical loads

As we mentioned before 3rd harmonics injection was used with PWM for harmonics reduction and lowering THD. In this paper we use different kinds of loads (resistive, induction and non-liner), during simulation, the loads will be added sequentially by the breakers as illustrated in Figure 1, so we can study the effects for loads nature on THD value and voltage amplitude. Also, adding load will affect the volage amplitude, so changing loads giving upportinity to test both pulsing technic and amplitude regulator for the proposed controller.

3. CASE STUDY SIMULATION

Small scale isolated RES with 10 kW WT and AC-DC-AC converter, and different loads have been simulated in MATLAB/Simulink. Figure 6 shows the full simulation for the system. The full simulation time is 5 sec, windspeed will change after 3 sec. The fist load will be in the system from the beginning, the second load will enter after 1 sec, the non- liner load will enter after 2 sec. These changes will affect the DC voltage after rectifying stage, so the controller in inverter stage has to adjust the AC voltage regardless what happen in the system.

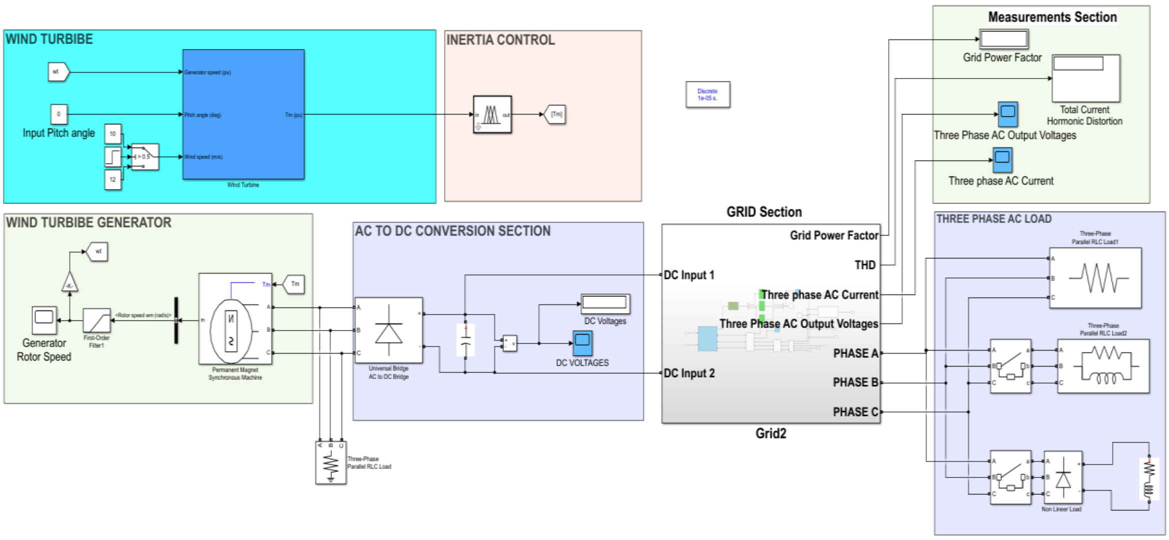

Figure 6. Inverter side full controller structure

4. SIMULATION RESULTS

4.1. With ordinary PWM controller

After the simulation for the full system in MATLAB/Simulink, the proposed structure is ready to tested under different operating conditions. PQ for voltage issues is very important problem in RES, this paper will concentrate on voltage amplitude, frequency, and THD value. Also, current THD in the load side. Figure 7 shows the simulation for ordinary PWM technic. Wind speed affects the output power from the PMSG which is connected to WT [20], that means with no excitation system the output voltage will change due to wind speed and load value, the AC voltage from PMSG will be rectified in the first stage from the converter, and will become the input for the inverter phase, Figure 8 shows the DC voltage during the simulation time.

DC voltage for the inverter should be greater than peak value of the AC output voltage at least by 10%, and this is clearly accomplished in Figure 8 [21], [22]. Without using controller for the inverter stage, the voltage amplitude will be greater than the acceptable value for isolated power system. Figure 9 shows the voltage amplitude in PU during the simulation time.

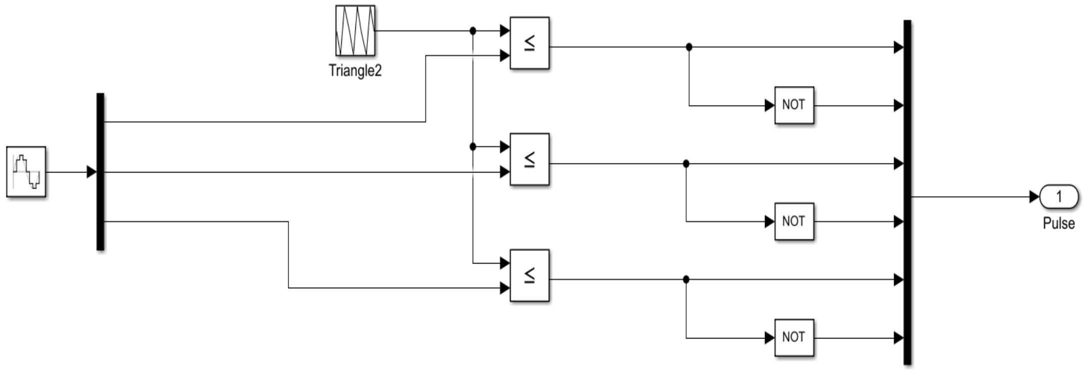

Figure 7. PWM technic for switches

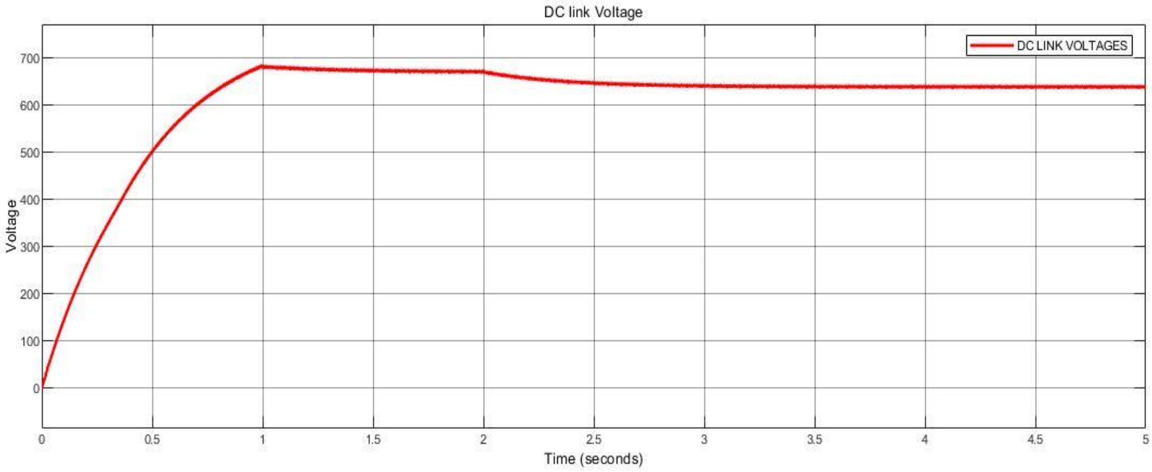

Figure 8. DC voltage in rectifier stage (PWM)

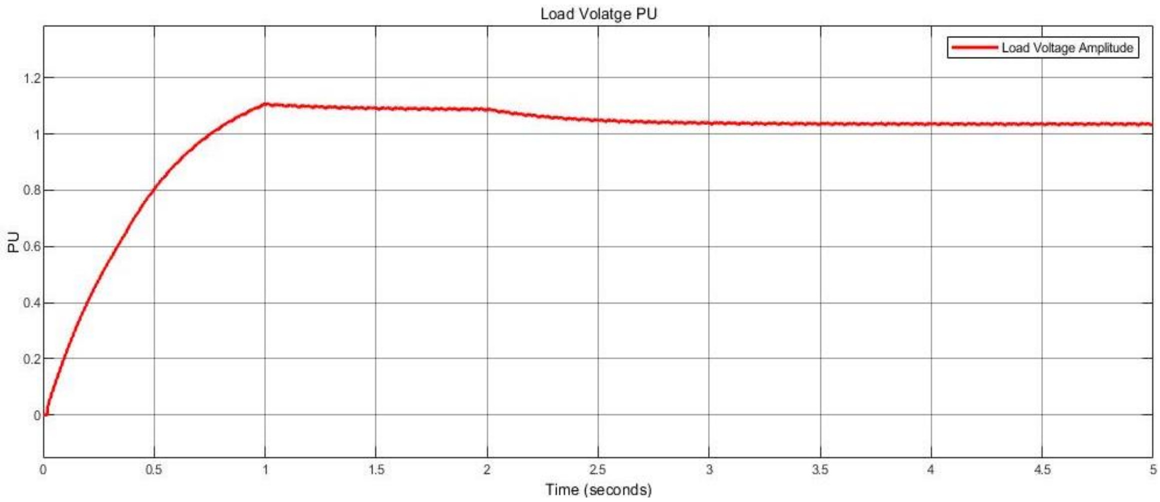

Figure 9. AC voltage amplitude at the load side (PWM)

Table 2 shows the voltage amplitude in PU for different wind speed with ordinary PWM. Figure 10 shows the voltage and current THD during different operating conditions. Table 3 shows the voltage/current THD for different loads. Figure 11 shows voltage wave in the load side before and after using LC filter. Figure 12 shows the current wave at the load side before and after filtering.

Table 2. The voltage amplitude with PU for different wind speed (PWM)

Case	Voltage amplitude (PU)
High wind speed	1.1
Normal wind speed	1.09
Low wind speed	1.07

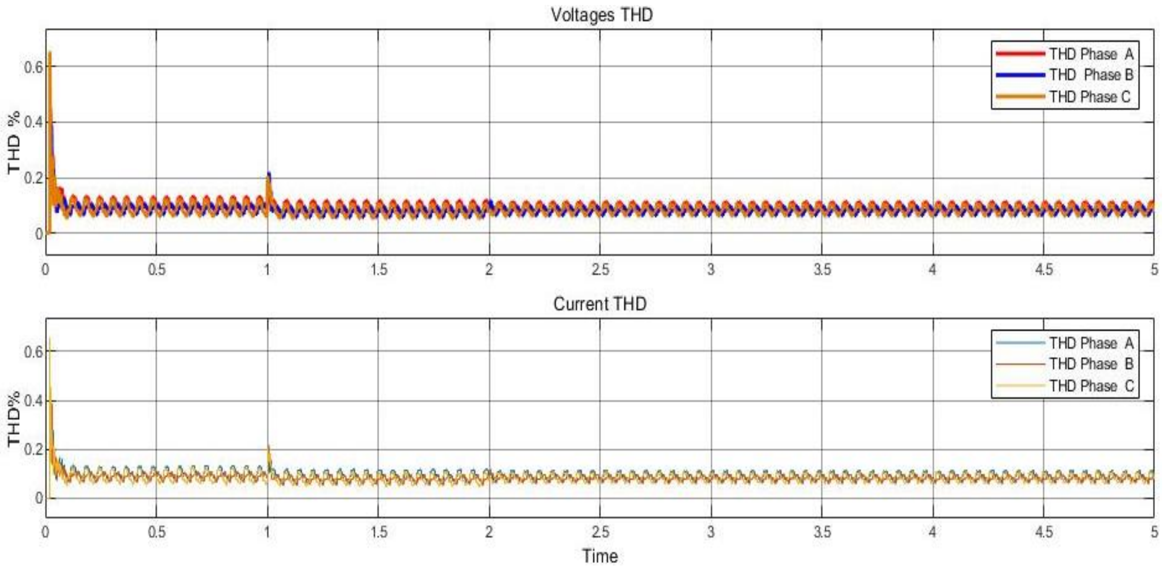

Figure 10. Current/voltage THD during simulation (PWM)

Table 3. Voltage/current THD for different loads (X)

Case	Voltage THD (%)	Current THD (%)
liner load	6	6
(Combined load active and reactive)	8	8
Non-liner load	10	8.5

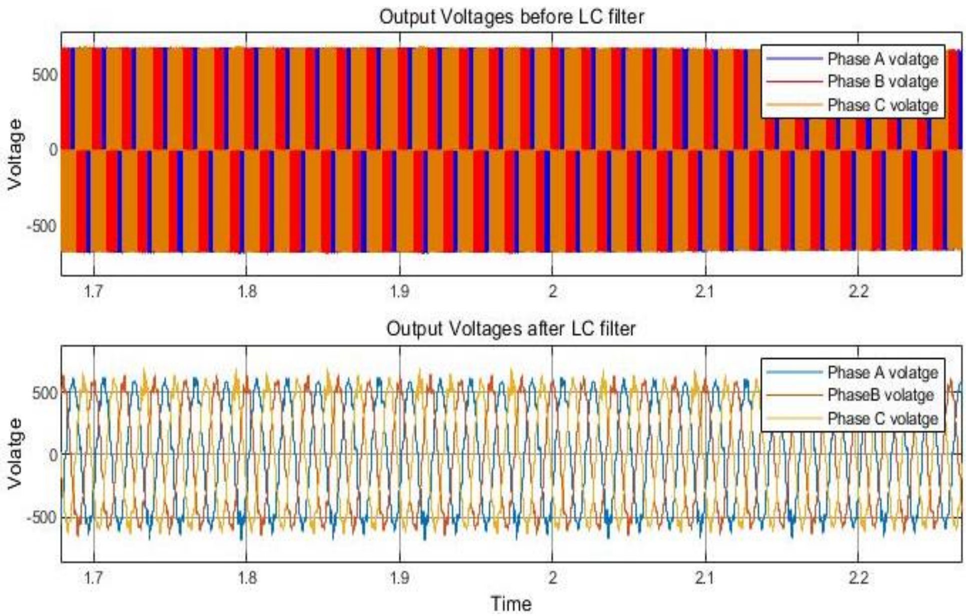

Figure 11. Voltage waveform before and after filtering (PWM)

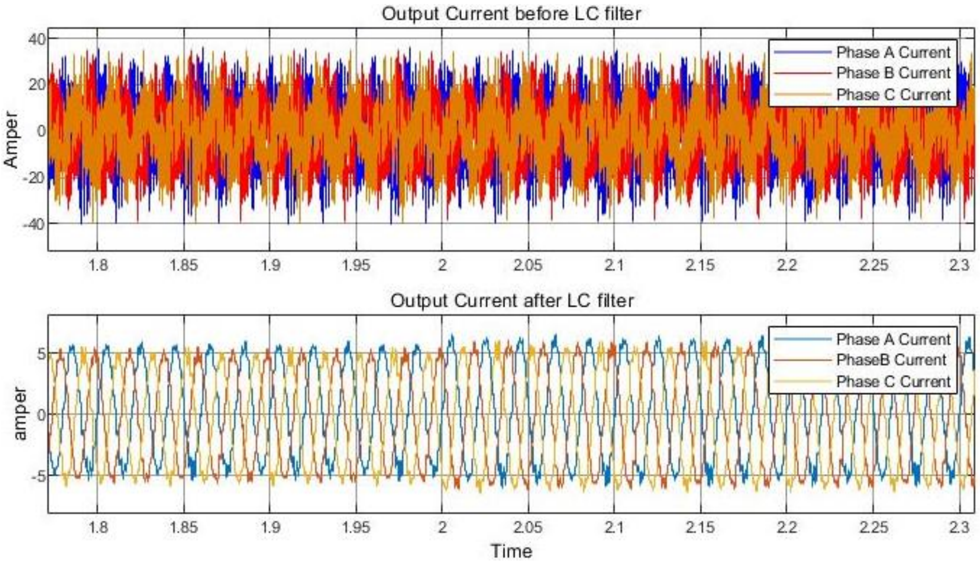

Figure 12. Current waveform before and after filtering (PWM)

4.2. Using PID with 3rd harmonic injection controller

The subsystem in Figure 6 has the simulation for the inverter stage with the controllers, which were made as Simulink general blocks so it can be used with different voltage values and applications. Figure 13 shows the simulation for inverter stage with the controller. The frequency for chosen carrier signal is 8 kHz. Figure 14 shows the DC voltage during the simulation time. In the inverting stage, a close loop PID controller will be used to regulate the amplitude for modeled signal, which leads to adjust the output voltage amplitude close to nominal voltage value of the load. Figure 15 shows the voltage amplitude in PU during the simulation time.

Form previous figure we can see that the PID controller with PWM was able to regulate the voltage amplitude close to 1 PU in spite of wind speed, and load changes. Table 4 shows the voltage amplitude with PU for different wind speed. THD is very important to be at acceptable value to meet the requirement of PQ in the stand-alone systems, high THD value means voltage/current waveform full with harmonics [23], Figure 16 shows the voltage and current THD during different operating conditions. Table 5 shows the voltage/current THD for different loads.

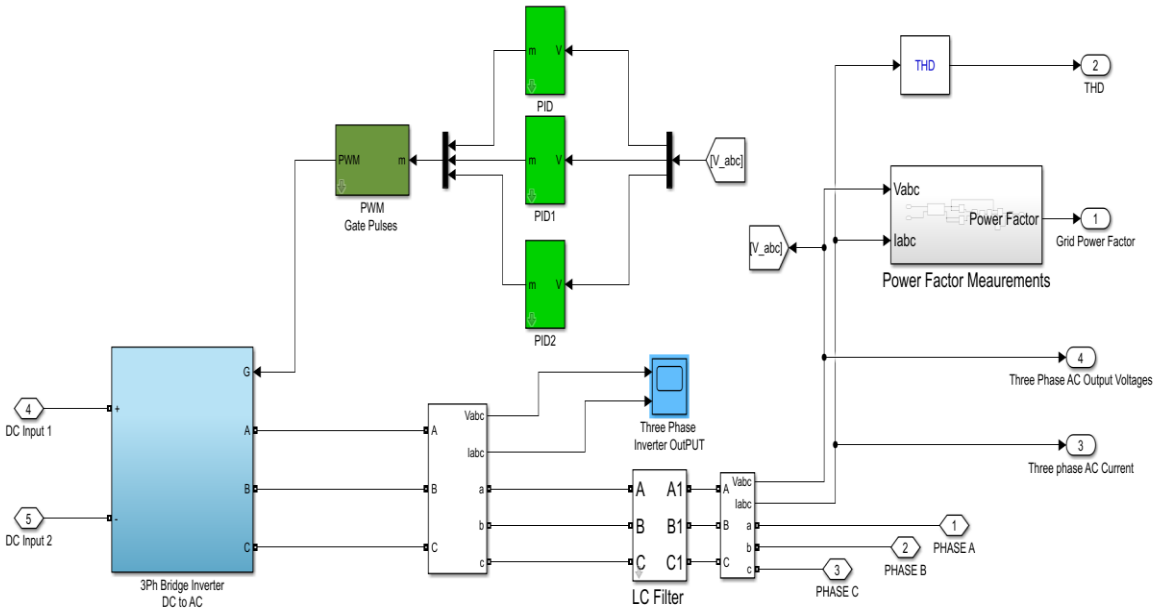

Figure 13. Inverter stage simulation in MATLAB/Simulink

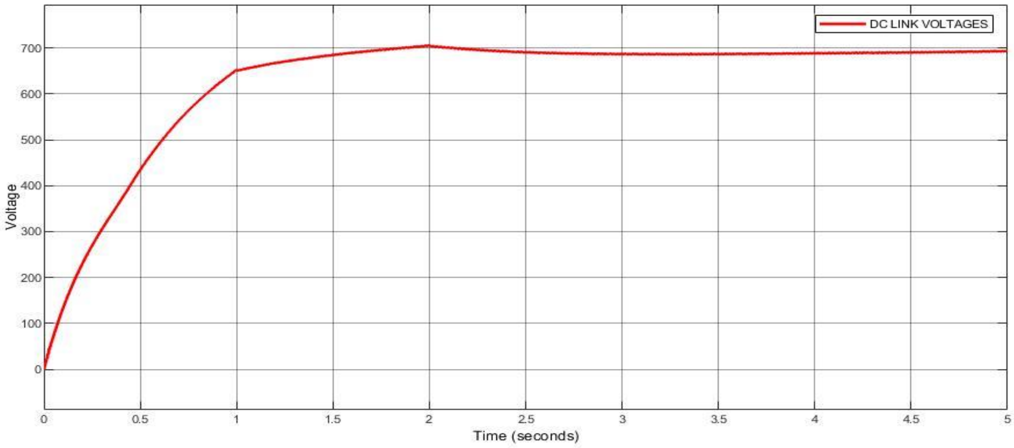

Figure 14. DC voltage in rectifier stage (proposed controller)

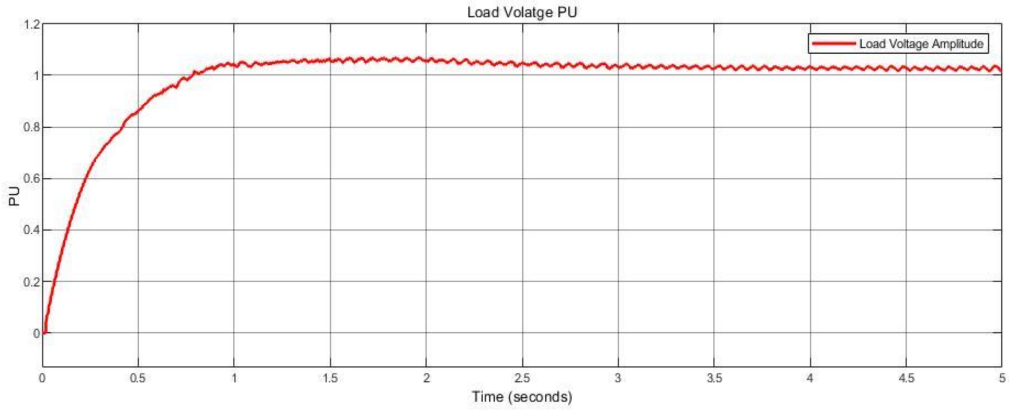

Figure 15. AC voltage amplitude at the load side (proposed controller)

Table 4. The voltage amplitude with PU for different wind speed (proposed controller)

Case	Voltage amplitude (PU)
High wind speed	1.03
Normal wind speed	1.02
Low wind speed	1

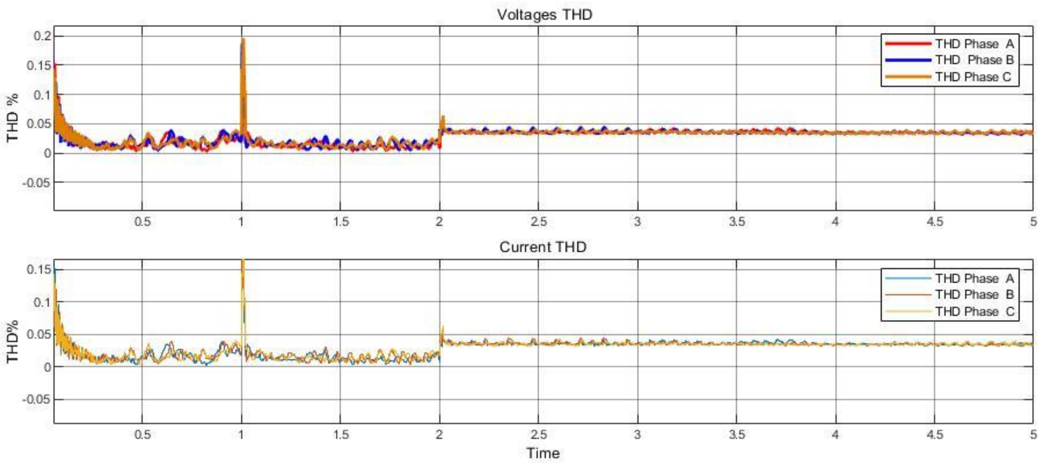

Figure 16. Current/voltage THD during simulation (proposed controller)

Table 5. The voltage/current THD for different loads (proposed controller)

Case	Voltage THD (%)	Current THD (%)
liner load	2	2
(Combined load active and reactive)	2	2
Non-liner load	3.5	3.6

Using 3rd harmonic injection led to lower THD in voltage waveform as illustrated in Figure 9, applying LC filter is very effective way to have sine wave [24], [25], Figure 17 shows voltage wave in the load side before and after using LC filter. It's worth to mention that using 3rd harmonic injection improve efficiency for in inverter by illuminating the needs for filtering 3rd harmonic component in the output. Figure 18 shows the current wave at the load side before and after filtering.

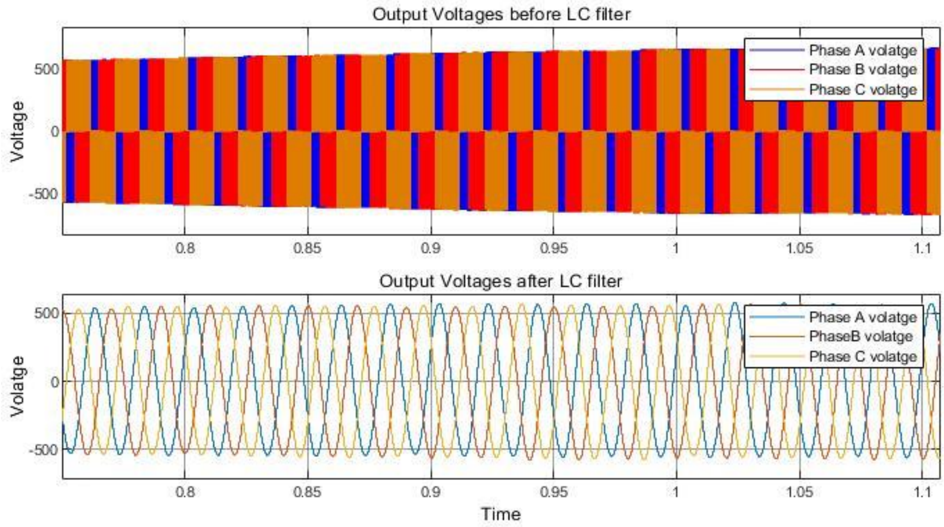

Figure 17. Voltage waveform before and after filtering (proposed controller)

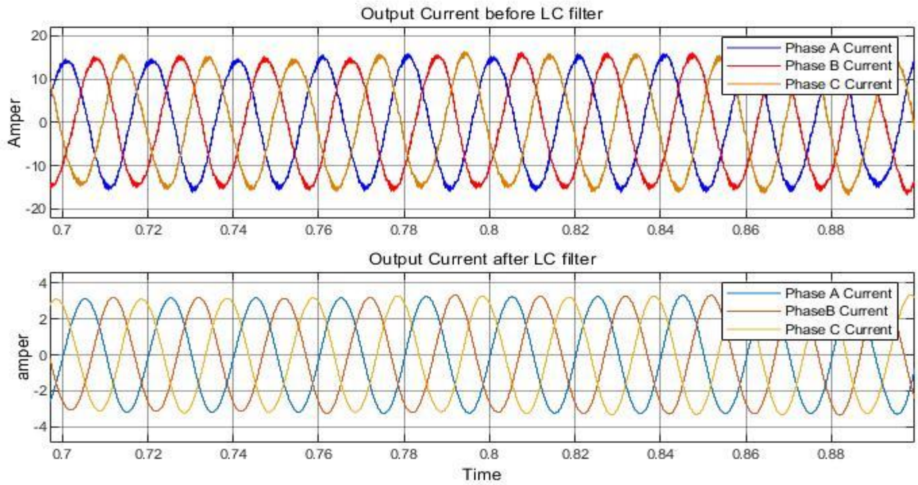

Figure 18. Current waveform before and after filtering (proposed controller)

5. RESULTS DISCTION

PQ becomes a major challenge with the high penetration of renewable energy generation in power system especially the isolated ones. AC converters plays key role for voltages amplitude regulation and THD. In this paper we focus on AC-DC-AC converter control strategy which has two sections, the first is using PID to regulate output voltage RMS with different wind speed values, and load factor. Second is 3rd harmonic injection for THD reduction, in this paper we have two PQ parameters we've deal with. For each parameter we perform a compression between PWM without regulation and proposed controller under different values for wind speed. Table 6 shows voltage amplitude compression for the two cases.

Table 6. Voltage amplitude compression for the two cases

Case	PWM	Proposed controller
High wind speed	1.1	1.03
Normal wind speed	1.09	1.02
Low wind speed	1.07	1

The second parameter is THD which is affected by load nature. Table 7 shows voltage/current THD compression for the two cases. Gannoun *et al.* [9] current THD was 2.99% with liner load, in [12] voltage THD was 2.78% and for current 4.06%, which means that the proposed structure can improve PQ for renewable energy systems (RESs), also according to IEEE 512-2022 voltage THD have to be less 8% and less 5% for individual harmonic and results were below this value for voltage THD.

Table 7. Voltage/current THD compression for the two cases

Case	PWM voltage THD (%)	PWM current THD (%)	Proposed controller voltage THD (%)	Proposed controller current THD (%)
liner load	6	6	2	2
(Combined load active and reactive)	8	8	2	2
Non-liner load	10	8.5	3.5	3.6

6. CONCLUSION

This paper presented an isolated power system with WT and PMSG, which feed different electrical loads. The proposed structure consternate on inertia controller at the WT side where fuzzy logic controller was used, and PQ parameters (amplitude-harmonics) for the output voltage at the load side by using PID controller with 3rd harmonic injection. The proposed power system was studied under different operating conditions for wind speed, loads nature and load values. From simulation results we can see that voltage amplitude was in range (1-1.03 PU), and voltage/current THD was between (2%-3.6%) during the simulation time, which indicates the effectiveness of the proposed controller for PQ improvement for isolated renewable energy power systems.

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BIOGRAPHIES OF AUTHORS

Goksu Gorel received received the M.Sc. degrees from Department of Electrical and Electronics Engineering, Trabzon, Turkey and received the Ph.D. degrees from Department of Electrical and Electronics Engineering, Kirikkale, Turkey, in 2017. Since 2018, he is working as an Asst. Prof. in the Department of Electrical and Electronics Engineering at Cankiri Karatekin University, Cankiri, Turkey. His current research interests include static var compensation power systems, renewable energy sources, solar power systems, load-frequency control, and new control strategy. He can be contacted at email: goksugorel@karatekin.edu.tr.

Inas Fadhil received the bachelor's degree from Department of Control and System Engineering, University of Technology Baghdad, Iraq in 2013. Since 2020, she is study as a master student in the Department of Electrical and Electronics Engineering at Cankiri Karatekin University, Cankiri, Turkey. She is currently working in Middle Technical University in Baghdad, Iraq. Her current research interests include renewable energy sources, simulation using MATLAB and deep learning, the areas of wind power and photovoltaic power, electrical machines drive, process control, senseless control of electrical machine, robust, and nonlinear control. She can be contacted at email: inas.fadhil@mtu.edu.iq.