Harmonic Distortion in an Off-Grid Renewable Energy System with Different Loads

M. Hojabri, M. Hojabri, M.S. Soheilirad

Abstract— **This paper is started by discussed and compare the structures of three linear controller namely PI, PID, PR and RC controllers in order to reach the control of renewable energy systems. And continue by implementation of a PID controller with PWM inverter for controlling a single phase off-grid renewable energy system. The analysis includes dynamic response, voltage harmonic distortion and current harmonic distortion for different resistive and inductive loads. The system is simulated using Matlab Simulink and simulation results demonstrate the different effects of renewable energy systems on voltage and current waveform with different loads.**

Index Terms— **linear controllers, PID controller, PWM inverter, renewable energy systems, harmonic distortion**

I. INTRODUCTION

Energy demand increasing makes important problems such as grid instability or even outage. Therefore, more energy must be generated at the grid. However, energy generation by big plant is not economically. Moreover, implementation of distributed generation is rapidly increased. Because of increasing global warming, limitation and high cost of fossil fuel sources, governments tend to increase use and implementation of renewable energy sources. The main difference between renewable energy and fossil fuels systems is up front cost versus lifelong energy cost. Currently, in most development countries, governments as well as utilities provide a variety of incentives, to help the renewable energy industry reach to a higher economic scale. However, renewable energy sources are not perfect, but they could be a good choice to replace with fossil fuels. However, environmental friendly is the principal advantages of renewable energies, high up front cost and uncontrollability are the main disadvantages of it. Renewable energy sources can be used as an off grid or on grid systems. Most type of renewable energy systems works in conjunction with the existing electrical grids.

The heart of a renewable energy system is a DC to AC inverter which adapts to the power grid voltage and frequency. So, inverter technology has an important role to have safe and reliable grid interconnection operation of renewable energy systems. It is also necessary to generate a high quality power to the grid with reasonable cost. For this reason, up to date technologies of power electronics are applied for renewable energy inverters. They must be capable of provide high efficiency conversion with high power factor and low harmonic distortion. Based on control policy, line-commutated or self-commutated inverter can be selected. A line communicated inverter is tied to a power grid or line. The commutation of power (conversion from DC to AC) is controlled by the power line, so that, if there is a failure in the power grid, the renewable energy system cannot feed power into the line. Self-commutated inverter is also divided to voltage source and current source inverter types. Voltage control scheme inverter, control the grid voltage. The current control scheme inverter controls the grid current. Compare to the current control scheme inverter, fault short circuit current for voltage current scheme is high.

It is important that any inverter system connected to the grid or directly connected to the load does not any significant way degrade the quality of supply at the point of connection. It is also important to consider the effects of a poor quality of supply on an inverter added to the power system or load. Unbalanced input supply voltages and impedances make odd harmonics in ac current [1]. According to the IEEE standards [2] and IEC [3], the Total Demand Distortion (TDD) of the current injected to the grid and the Total Harmonic Distortion (THD) of voltage should be lower than 5%. Then, different control methods are proposed to obtain lower harmonic distortion. The IEEE standard of voltage and current harmonic distortion limits is presented in Table I and Table II. The important aim of this paper is to give a comprehensive description of current control techniques for grid connected converters and comparison them according to their performance like steady state error, transient response and harmonic compensation. This paper is organized as follows. Inverter control techniques introduced in Section II, performance overview of linear control techniques in Section III, simulation results of the case study will be explained in section IV, power quality analysis for different loads in section V and finally, some conclusions are given in section VI.

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TABLE I
IEEE STANDARD CURRENT DISTORTION LIMITS [5]

Isc/IL	<20	20<50	50<100	100<1000	>1000
h<11	4	7	10	12	15
11≤ h <17	2	3.5	4.5	5.5	7
17≤ h <23	1.5	2.5	4	5	6
23≤ h <35	6	1	1.5	2	2.5
35≤h	0.3	0.5	0.7	1	1.4
Total Dema Distortion (TDD)	5	8	12	15	20

Isc: Maximum Short- Circuit Current
IL: Maximum Demand Load Current

TABLE II
IEEE STANDARD VOLTAGE DISTORTION LIMITS [5]

Bus Voltage	Individual Voltage Distortion (%)	Total Harmonic Voltage Distortion (THD %)
V< 69 kV	3	5
69 kV< V< 161 kV	1.5	2.5
161 kV ≤V	1	1.5

II. Inverter Control Techniques

A General block diagram of grid connected renewable energy system is presented in Figure 1. Control of this system can be applying in input-side or grid-side. The main task of the input controller is to extract the maximum power from the renewable energy sources and protect the input side converter while, the grid side controller must check the active and reactive power which is transferred from renewable energy systems to the grid. Grid synchronization and controlling the power quality of power injected into the grid are another duty of the grid side controller.

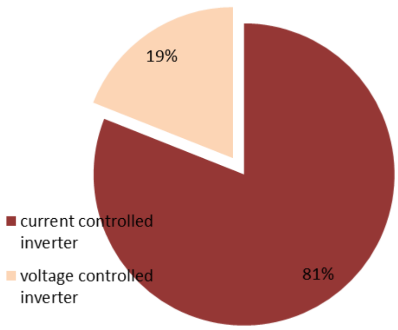

Fig. 1. Current and voltage control scheme inverter ratio.

Based on the literature review, the self-commutated voltage type inverter is employed in all inverters, with a capacity of 1 kW or under, and up to 100 kW. By using a simple control circuit, current control scheme inverter can be achieved a high power factor. Therefore, the current control type inverters are more popular. In the current control scheme inverter, performing as an isolated power source is difficult, but there are no problems with grid interconnection operation [4]. The operations of the current controlled type inverters are depended on use of the current control technique types. Renewable energy system control techniques can be classified into two main groups of the linear and nonlinear techniques. The most famous linear current control techniques are Proportional Integral (PI)[5–9], Proportional Integral Derivative (PID), Proportional Resonant (PR) and Repetitive Controller (RC). Predictive [10-11], dead beat and hysteresis [12] are the nonlinear controller.

A. Proportional Integral (PI)

Proportional (P) controllers were used as former inverter controller. However this kind of controllers has an inherent steady-state error [13]. The P controller's steady state error was eliminated by adding integral component to the transfer function [14]. Therefore, the average value of current error reduced to the value of zero by changing the integral components. Even so, the current errors can appear in transient conditions. Transient response of the proportional integral (PI) controller is limited by the proportional gain. Then the gain must be set at a value that the slope of the error is less than the slope of the carrier saw tooth waveform required for generating the firing pulses of the inverter. Most of the PI controller's applications are in dq control, since they have an acceptable performance while regulating the dc variable. A PI controller gain is determined via (1):

$$G_{PI}(s) = K_P + \frac{K_i}{s} \quad (1)$$

Where K_P and K_i are the proportional and the integral gain of the PI controller. The controlled current has to be in phase with the grid voltage. Therefore, the phase angle used by the abc→dq transformation module has to be extracted from grid voltages. However, PI controller is mostly used in dq control, but it could be used in abc frame as well. The related matrix transfer is presented in [15]. To overcome on transient respond to the problem of the PI controller, an average current mode control (ACMC) was introduced. Since the additional derivative component which was used in ACMC not only the steady state error removed, but again the fast transient response achieved. Consequently, the regulator gain improves at the switching frequency. However, this method has the problem of high frequency sub-harmonic oscillations with the current mode control and its instability is reported under a certain conditions, too. A PI controller compensation operates as low and high pass filters [16]. Under unbalanced conditions, harmonic compensators for both positive and negative sequences of each harmonic order are required. For instance, four compensators are needed for the fifth and seventh harmonics compensation. Hence, their control algorithms become complicated.

B. Proportional Integral Derivative (PID)

A PID controller is a feedback controller meant to keep the desired output constant. A block diagram of a PID controller is shown in Figure 2. The PID controller calculates an error signal e(t) by comparing the output c(t) with the desired reference output r(t). The controller attempts to minimize e(t) by adjusting the control inputs.

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The output, u(t), and transfer function, G(s) of a PID controller is defined by:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \quad (2)$$

$$G(s) = \frac{U(s)}{E(S)} = k_p + \frac{k_i}{S} + k_d S = k_p(1 + \frac{1}{T_i S} + T_d S) \quad (3)$$

Where k_p is the proportional gain, k_i is the integral gain, k_d is the derivative gain and T_i and T_d are the integral and derivative times of the PID controller, respectively. In Simulink model of the PID controller, the three controller parameters, k_p, k_i and k_d must be determined. Simulink provides a tool for automatic tuning of the PID controllers to follow the desired output.

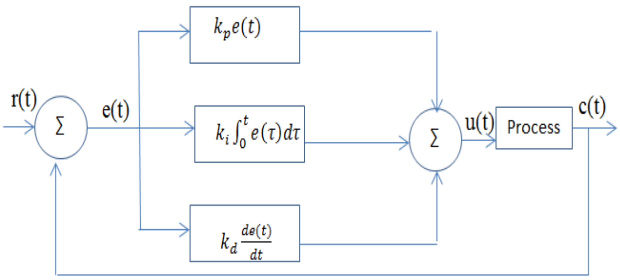

Fig. 2. A PID controller block diagram.

C. Proportional Resonant (PR)

The ideal proportional resonant controllers (PR) [17–20] widely used in abc directly when the control variables are sinusoidal. PR controllers present a high gain around the natural resonant frequency of ω, which is presented by (4).

$$G(s) = K_p + \frac{K_i s}{s^2 + \omega^2} \quad (4)$$

Where ω , K_p and K_i represent the resonance frequency, proportional and the integral gain of the PR controller. This controller achieves a very high gain about the resonance frequency. Therefore it can omit the steady state error between the reference and the controlled signal. The width of the frequency band about the resonance point depends on the integral time constant of K_i. A low K_i can cause a narrow band, while a high K_i causes a wider band. The high dynamic performances of a PR controller have been described in different papers such as [21]. The PR controller harmonic compensation can be achieved by cascading several generalized integrators, which are tuned to resonate at the specified frequency. Therefore, selective harmonic compensation at different frequencies can be achieved. A typical harmonic compensator (HC) has been introduced for compensation of the third, fifth, and seventh harmonics [22]. The transfer function of the HC is shown in (5):

$$G_h(s) = \sum_{h=3,5,7} K_{ih} \frac{s}{s^2 + (h.\omega)^2} \quad (5)$$

Where ω is the natural resonance frequency, h is the harmonic's number and K_{ih} is the integral gain of the related harmonic. Then it is simple enhance to the abilities of the scheme, by adding harmonic compensation properties with more resonant controllers in parallel to the main controller. In this case, the harmonic compensator works on both positive and negative sequences of the selected harmonic. Therefore, only one HC is needed for one harmonic order. Moreover, another advantage of the HC is that it does not affect the dynamics of the PR controller, and it just has an effect on the frequencies that very close to the resonance frequency. However, since the distorted currents usually contain more than one order harmonics, it would be preferable to use many resonant compensators, which are tuned at different harmonic frequencies, and cascaded together or nested in different rotating reference frames to achieve the multiple harmonics compensation.

D. Repetitive Controller (RC)

Another kind of the grid connected controllers is repetitive controller (RC) which can omit the steady-state error by periodic controlling of the components. The RC controllers achieve a large gain at the integral multiples of fundamental frequency. The RC controllers like sliding mode [23-26], odd-harmonic repetitive controller [27] and dual-mode repetitive controller [28] are introduced to obtain the dynamic response. These repetitive controllers are implemented as harmonic compensator and current controller, to track the fundamental reference current. However, RC controllers can cause a slow dynamic response and they are applied only in the static mode.

III. Performance Overview on Inverter Linear Control Techniques

Control techniques help inverters to provide stability, low steady state error, fast transient response and low total harmonic distortion when renewable energy sources are connected to the grid. Among linear grid connected controllers, the PI controller has a large gain at low frequencies where the PR controller gives the highest gain about resonance frequency, and RC achieves its high gain at the integral multiples of the fundamental frequency. This group of controllers are well known to eliminate the error. However, their dynamic response is not enough good compared to nonlinear controllers. Among linear controller techniques RC has the lowest transient response, and PR is the fastest one. Because of the dq control structure of PI controllers, their ability to compensate the harmonics is based on using low pass and high pass filters. However, a harmonic compensator for each harmonic order is necessary. Then, the control algorithm is become complicated. In overall, PI controllers are poor in eliminating the current harmonics. PR controllers as PI controllers are unable to give a large loop gain at the multiple harmonic frequencies to provide a good compensation for a wide band of harmonics. In linear controller group, RC gives a simple and practical solution for multiple harmonics compensation. A summary of comparison between linear controller techniques is shown in Table III.

TABLE III
Inverter Linear Control Techniques Comparison

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	PI, PID	PR	RC
High Gain	at low frequencies	around resonance frequency	at the integral multiples of the fundamental frequency
Steady State Error Elimination	Very Good	Very Good	Very Good
Dynamic Response	Fast	Very Fast	Slow
Harmonic Compensation	Poor	Poor	Good

Nonlinear controllers are famous for their dynamic response. This group has a fast transient response. Then, they can eliminate the low order current harmonics. It must be considered that the current waveform will carry harmonics at switching and sampling frequency's order. In this case, fast sampling capability of the hardware used is necessary. The famous nonlinear control techniques are predictive control, dead-beat control and hysteresis control.

III. Simulation Results

A complete Simulink model for an off-grid renewable energy system with a pure sine wave inverter and an inductive load is presented in Figure 4. The major parameters used in this Simulink model are shown in Table IV. In this simulation, a PID controller is used to control the output voltage of the inverter. A variable step discrete with a sampling time of 1 μs was chosen. A variable step solver shortens the simulation time of a Simulink model significantly by reducing the number of steps as necessary, by adjusting the step size for a given level of accuracy [29]. A switch was placed before the motor to analyze the motor performance at the instant of turning OFF and turning ON. A timer set a fixed timing for the switch to open and close. Scopes were placed to view the voltage and current waveforms at different nodes in the circuit.

The Simulink model of a single- phase PID controller is shown in Figure 3. The reference sinusoidal single of amplitude 170 V, generated by the trigonometric function 'sin' block in the model, is compared with load voltage. Then, the error signal is fed to the PID controller. The output of the PID controller will be used as the reference signal for inverter, which generated appreciate pulses to control the inverter switches.

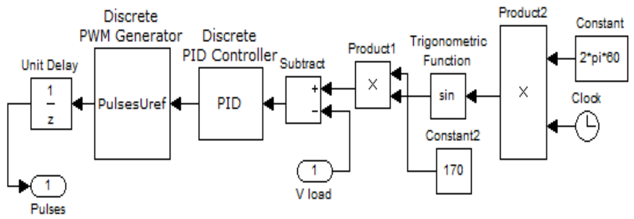

Fig. 3. Simulink model of PID controller.

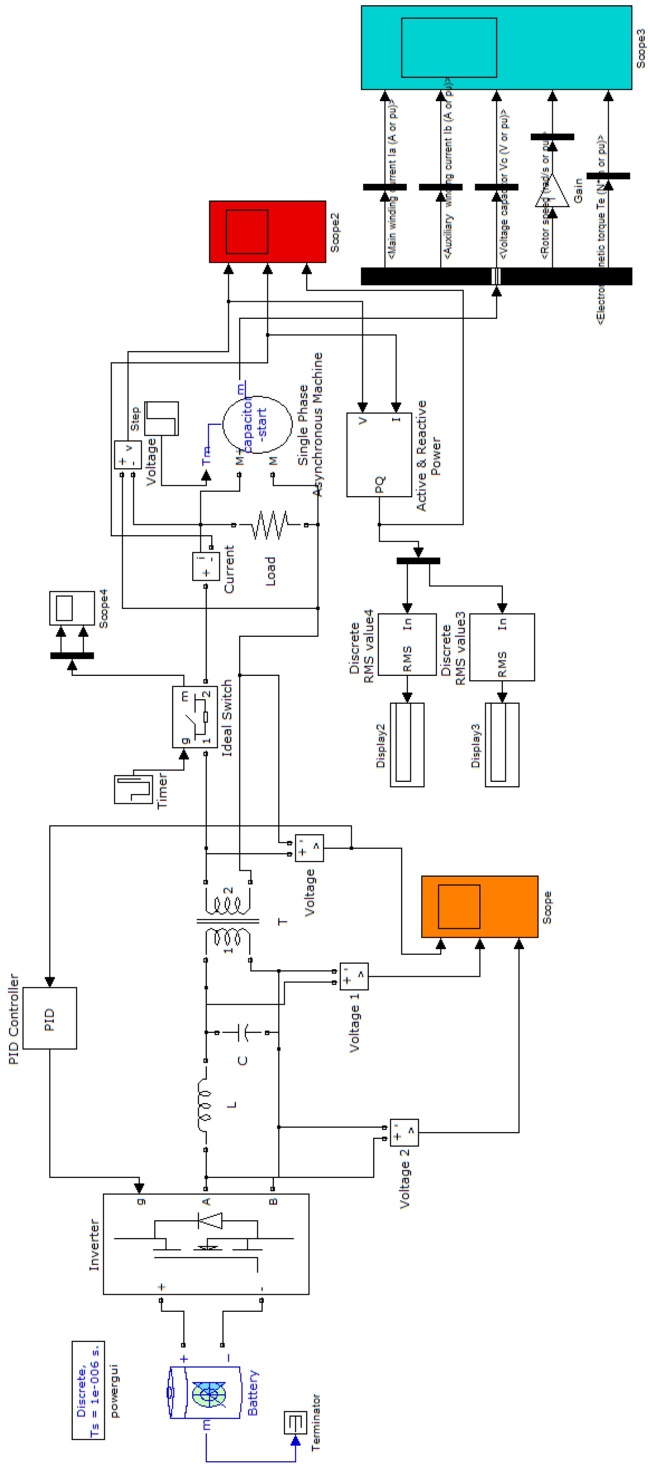

Fig. 4. A Simulink model of an off-grid renewable energy system.

The simulation has done for a single-phase inductive load (100 W, 200 var). In this case, the three subplots represent the voltage waveform, current waveform and the power for the load, respectively. When the switch was turned ON at T = 0.4 of a second, a current of almost 2.65 A was drawn by the motor while maintaining an output voltage of 119 V. A high amount of power (active power of 98.21 W and reactive power of 196.4 var) was drawn by the load at that time, compared to its power rating of 100 W.

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TABLE IV
MAIN PARAMETERS OF SIMULINK MODEL

Device	Parameters
Battery	24 V
Inverter	Cut-Off Frequency=100 Hz, Switching Frequency = 2 kHz
LC Filter	0.362 F, 7 µH
Transformer	4 kVA, 60 Hz, 20:120

The simulation results did not show any voltage sag caused by the inductive load during normal operation. The simulation also predicted a much larger transient at turn-off due to the idealized instantaneous change in current. The gate pulses for each inverter switch were generated by the PWM generator as shown in Figure 5. Only a pair of switches (S1 and S4) or (S2 and S3) were turned ON at any instant of time. For example, at 0.035 sec, switches S1 and S4 were ON while S2 and S3 were OFF. The widths of the generated pulses were varied to ensure that their averaged output produced a 60 Hz sinusoidal waveform.

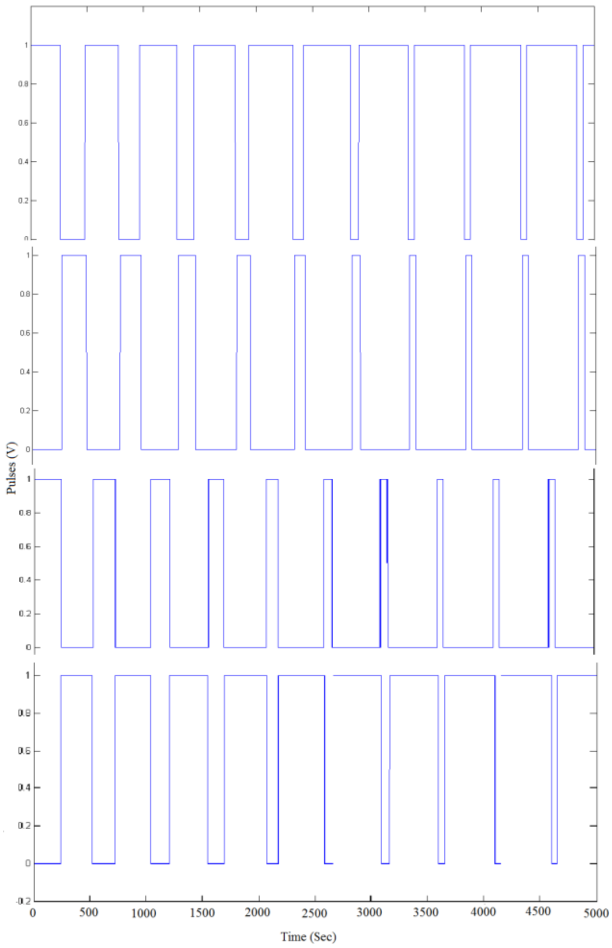

Fig.5. Gate pulses of inverter switches S1, S2, S3 and S4.

The higher frequency components in the PWM output of the pure sine wave inverter were filtered using a low pass LC filter with cut-off frequency 100 Hz, and then the resulting sine wave was passed through a step-up transformer. The peak value of the primary voltage was close to the battery voltage. The voltage transients that occurred at the instant of switching OFF the motor load travelled to the secondary side of the transformer. The secondary winding of the transformer experienced a voltage transient of nearly 170 V on the positive half cycle and -210 V on the negative half cycle at 10 sec. The transient voltage, however, did not travel to the transformer's primary side because of its nearly instantaneous duration, the absence of parasitic capacitance in the secondary winding in the model, and also because of the absence of a direct physical connection between the two windings [30].

Using the FFT analysis tool in Simulink, the THD of the output voltage and current waveforms were recorded. The results shows the voltage harmonics for the inductive load (100W, 200 var) supplied by the pure sine wave inverter, in which case the THD value was 7.63 % for normal operation. As the low pass filter eliminated the low order harmonics well, some higher order harmonics were still seen, but with small magnitudes. The THD for the current waveform during the normal operating condition was 3.68 %. The voltage THD value is well above the IEEE standard of 5%. But the current harmonic distortion is still less than 5%.

IV. Power Quality Analysis for Resistive and Inductive Loads

The system power quality effects from other devices were observed by replacing the motor load with a parallel RL load of different power ratings. The loads were turned ON at 0.5 sec to allow time for the inverter transients to settle down, and the loads were turned OFF at 1.08 sec. When the load switch was turned OFF, large voltage transients were seen with the parallel RL load as they were with the motor load, due to the unrealistic, instantaneous change in the modelled current. For example, voltage transients of 350 kV occurred when an inductive load (500 W and 750 var) was used. This voltage transient caused a negative voltage transient of magnitude 1100 V at the secondary side of the transformer. However, there were no transients seen for a purely resistive load, due to its linear relationship with current. Inductive loads (which are the dominant reactive load in a residential setting) can therefore be assumed as the primary source of voltage transients. The simulated instantaneous change in current through the inductor is responsible for generating this high voltage transient according to the relation [31]:

$$V = L\frac{di}{dt} \quad (6)$$

Where V is voltage induced across the inductor, L, due to changing current di/dt. High start-up currents are drawn by the inductive loads to energize their coils. However, none of the purely resistive loads or loads where active power dominated the reactive power drew high start-up currents, as expected. For purely resistive loads, the simulation results showed that the current and voltage harmonics decreased slightly with heavy loads. For inductive loads also, voltage harmonics decreased while the current harmonics increased with heavy loads because of the high fundamental current draw. Table V summarizes the THD of the current and voltage waveforms for different simulated loads and the corresponding voltage transients that appeared in the system.

This simulation shows the off-grid loads had significant current and voltage harmonics due to the inverter's voltage along with the power electronics used in those loads. So the load's voltage and current harmonic distortion increase by increasing the pure resistance load. For inductive loads, the total current harmonic distortion is in IEEE standard range. But the voltage THD is out of IEEE standard range (more than 5%).

TABLE V
SIMULATION RESULTS FOR CURRENT AND VOLTAGE HARMONICS FOR DIFFERENT LOADS

Load	Total Harmonic Voltage Distortion THD %	Total Demand Distortion TDD %
No Load	7.45	----
150W	7.68	7.68
500W	8.17	8.17
700W	8.56	8.56
100W, 200 var	7.63	3.68
300W, 500 var	7.87	3.91
500W, 1000 var	8.18	3.93

V. CONCLUSION

In an off-grid renewable energy system, the end user appliances are becoming more sensitive to the power quality. In this paper, after a review on famous linear controllers which are using for controlling renewable energy systems, simulation has done for an off-grid system using PWM inverter and a PI controller to show the power quality consideration for different resistive and inductive loads.

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