PV&TEG Hybrid System controlled with Fuzzy based MPPT

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***Abstract*— In daily life, electrical power is very important source to maintain our works. The all working branch uses technological devices, and the nearly all technological devices use electricity as a supply. This situation has been increased our energy demand during passing time. The electricity mostly produced by using limited hydroelectrical generators, fossil fuel-based generators, and independent renewable energy systems. Our aim is to design a system that use PV, TEG as a source and the control method is fuzzy logic control. The fuzzy logic is one of the artificial intelligent systems and it is relatively new control method. The system is designed for the supply the AC loads. In the system full bridge inverter is used to supply three different loads. The result shown that system (total circuits) efficiency 98.8%.**

Keywords—PV, TEG, Hybrid, Fuzzy Logic Control, Boost Converter, Full Bridge Inverter, Sinusoidal Pulse Width Modulation

I. Introduction

The energy is very essential component to our lives. Nearly all devices need to energy to continue its working condition. For technological devices, this energy will be compensated by using electrical energy. For this reason, the electrical energy production is important. This energy will be produced efficiently, clean and sustainable by using renewable energy sources. Because of these reasons, the new combination of the energy sources will become more important. Our aim is to produce electrical energy from PV-TEG hybrid system fed 3 different AC load via full bridge inverter. This type of hybrid system is very popular according to literature, but the proposed system has not researched much.

The first study about PV-TEG system was performed in 2004 and different types of semiconductor materials, solar panel area and collector were examined [1]. Ammar *et al.* prepared an article that examine PV/T panel, track optimum thermal and electrical power form artificial neural network [2]. Other study was done by Al-Azzawi & Tutunji and it is related with current control for thermoelectric generator (TEG), cooler for PV panel to improve of performance [3]. Another research about PV/TEG application was presented by using sliding mode control under dynamic disruption solar radiation and temperature difference [4]. The other study was about using PV-Thermal Interface Material and TEG device from using different cooling material, voltage and temperature variance [5]. Fini *et al*. wrote an article that tried to improve efficiency of PV-TEG system. According the paper's result the average maximum photovoltaic temperature according to experiment and simulation, the energy production of the system, electrical and exergy efficiency, and carbon payback period and discounted payback period was found [6]. These studies will be extended, but the hybrid topic and especially the PV-TEG system's importance will be seen soon.

There are also [7-11] articles that are related to PV-TEG hybrid system. In [7] the critical factors and parameter of PV-TEG system was examined. The [8] study is a review study about TEG-PV system. The [9] article designed a hybrid system that used organic PV and Organic TEG. In the study [10], the different types of PV-TEG hybrid system, different type of TEG devices and different type of heat transfer was mentioned. In the article [11], the hybrid PV-TEG system was examined for machine learning based MPPT control.

The other important topic is PV panel modelling. In this study, one of the sources was PV panel and the model is most important part to understand the behavior of the source. Sera *et al*. wrote a conference paper about modelling the PV panel from datasheet values. In that paper, some important formulas and the flowchart of the PV panel parameters was obtained [12]. Onat & Ersoz presented a symposium paper related with modelling PV panel and the compared different Maximum Power Point Tracking Methods (MPPT) [13]. Edouard & Njomo wrote an article that both model and simulate of the PV solar panel by using MATLAB Simulink [14]. Caglayan & Kayisli performed a study that examine PV panel behavior under Twisting Sliding Mode Control based MPPT, also the PV panel was detailly investigated [15]. The second source is Thermoelectric Generator (TEG) in our study. The TEG-s working principle, structural information and Theorical Model were mentioned in a book chapter [16]. Belkaid *et al.* presented a conference paper that both model the TEG device and simulate the TEG device which was controlled by Sliding Mode control [17]. The other conference paper was about modelling the TEG device and Kalman Filter was used to improve the performance [18]. Mamur & Coban wrote an article that examine detailly model of TEG. In this paper, TEG devices connected directly to the load via a boost converter and controlled with P&O Control [19]. To additional these sources there are sources [20-21]. In [20], The PV inverter was used for converting electricity which was produced by TEG to AC power. [21] was a thesis study that examine the effect of energy production efficiency of TEG density for hot air flowing close areas.

Mnati *et al*. wrote a conference paper that review different types of MPPT methods for PV systems. The comparative analyses were performed by using P&O Control, Incremental Conductance (IC), Constant Voltage (CV), Fractional order Open-Circuit Voltage (FOCV), Fuzzy logic (FL) and Artificial Neural Network (ANN) [22]. Another study aimed to classify and summarize of PV systems and controls were Traditional Methods and Intelligent Methods and under Partial Shading Conditions with MPPT [23]. The other classification and review article was written by Baba *et al.* and they aimed to compare of different methods [24]. The other conference paper was aimed to increase PV system performance by using highly efficient FL control and performed by Belkaid *et al.* [25]. Guenounou *et al.* wrote a paper about optimization of FL via Hierarchical Genetic Algorithm [26]. Another article was written by Tozlu & Calik to review and classify the most used MPPT algorithms [27] and similar researches about FL control have been performed [28-30]. The other important source of the fuzzy control sources was MATLAB videos. In these videos the fuzzy logic control mechanism and the control type was explained. [31-34]. And also, there are some other studies about hybrid sources in literature [35-36].

In this study, The Hybrid PV-TEG renewable energy system was designed and boost converter topology is used to convert DC renewable energy to another level DC power. The other converter is full bridge inverter that convert DC power to AC power. The Fuzzy Logic Control was selected as Maximum Power Point Tracking (MPPT) Method. The Sinusoidal Pulse with Modulation (SPWM) control is selected as inverter control. Three different load supplied systems power efficiency according to source produced power to load power was 98.8%. The block model of the proposed design is shown in Fig.1.

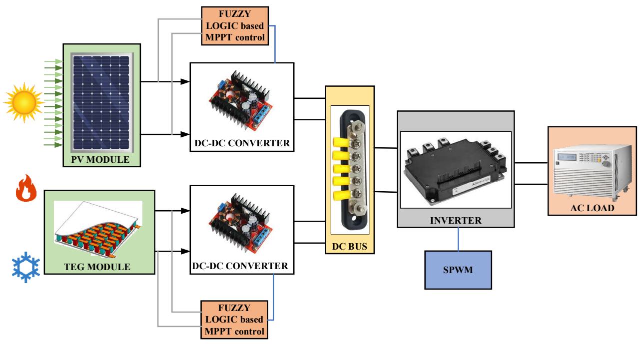

Figure 1. Proposed System Model

II. Boost Converter

The main voltage of renewable energy sources is generally DC and for the PV and TEG sources, dc-dc converter circuits are required to convert the produced dc level to another level (up, down or both). In this study, boost converter is preferred for this work due to its simple and well-known structure. The basic circuit diagram of boost converter is shown in Fig.2.

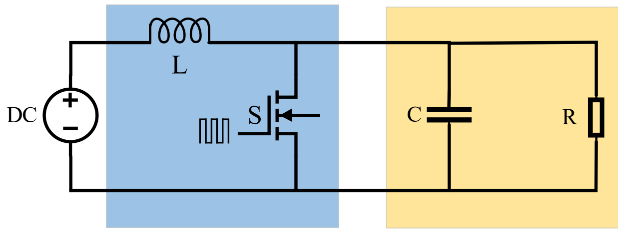

Figure 2. Boost converter circuit

The mathematical model of boost converter can be obtained by using basic equations depend on the on-off situation of the power switch [37]. For the off state of switch, the Eq.1, Eq.2, Eq.3, Eq.4 and Eq.5 are given;

$$I_c = C * \frac{dv_C}{dt} \quad (1)$$

$$\frac{1}{C} * I_c = \frac{dv_C}{dt} \quad (2)$$

$$\frac{dv_C}{dt} = \frac{1}{C} * I_c \quad (3)$$

$$\int \frac{dv_C}{dt} dt = \int \frac{1}{C} * I_c dt \quad (4)$$

$$v_c(t) = v_c(0) + \frac{1}{C} * \int I_c * dt \quad (5)$$

For the on state of switch, the Eq.6, Eq.7, Eq.8, Eq.9 and Eq.10 [37] are given;

$$v_L = L * \frac{di_L}{dt} \quad (6)$$

$$\frac{1}{L} * v_L = \frac{di_L}{dt} \quad (7)$$

$$\frac{di_L}{dt} = \frac{1}{L} * v_L \quad (8)$$

$$\int \frac{di_L}{dt} * dt = \int \frac{1}{L} * v_L * dt \quad (9)$$

$$i_L(t) = i_L(0) + \frac{1}{L} * \int v_L * dt \quad (10)$$

Also, the current and voltage ripples can be changed by using Eq.11 and Eq.12 [15].

$$\Delta i_L = \frac{V_L(t) * d * t_s}{L} = \frac{V_o(t) * (d - d^2) * t_s}{L} \quad (11)$$

$$\Delta v_o = \frac{I_o * d * t_s}{C} \quad (12)$$

III. Full Bridge Inverter

The AC load fed by a full bridge inverter circuit and its dc-link voltage is obtained from the output of boost converter. The full bridge inverter has two half bridge inverter that controlled by reverse signals, so the half bridge's output is half of the input voltage, however the full bridge inverter converts the DC voltage as maximum peak value of the AC signal. Sinusoidal Pulse Width Modulation technique is used to get the required PWM signals for power switches.

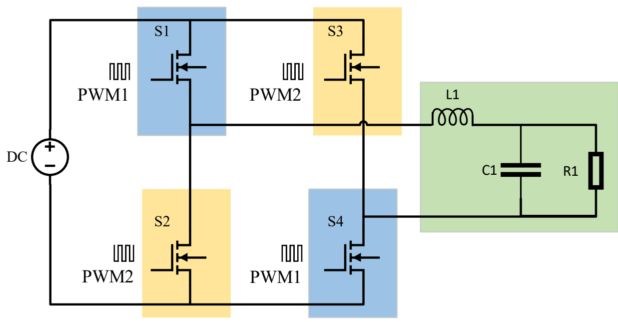

Figure 3. Full bridge inverter topology

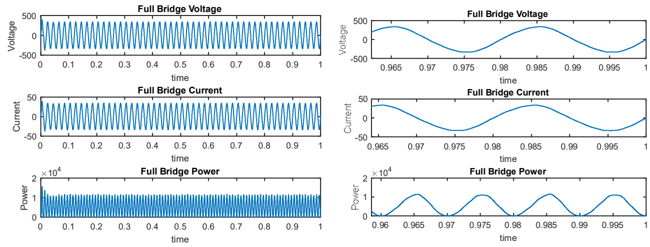

Figure 4. Full bridge inverter voltage, current and power signals

In the study there are two option to convert DC energy to AC energy. One of them is half wave inverter topology. The other is full wave inverter topology. In the half wave topology one of the paths is coming from the half part of the inverter the other is created by two capacitors in the supply side or for multiphase system. The loads ground is connected to each other. The outputs peak value of the half wave inverter is half of the dc side voltage value. This is increased the voltage demand and this topology is not suitable for transformer usage (the aim of the transformer is isolate the load side and supply part, but in this topology the ground is not a part of the inverter).

In the AC part the aim is to obtain AC value with minimal effect for source side. Because of that reason, the full wave inverter is selected. Full wave inverter output peak voltage value is equal to supply side voltage value. In the full wave inverter + channel and ground are obtained directly to the full wave branches, and the supply part is not affected directly by the AC side (The ground is not connected to the dc side).

IV. Renewable Energy Sources

A. PV Panel

PV Panel is a device that convert light or sun light to the electrical energy. If the light has enough energy the system starting the work. In the Fig.5, equivalent model of PV panel is shown.

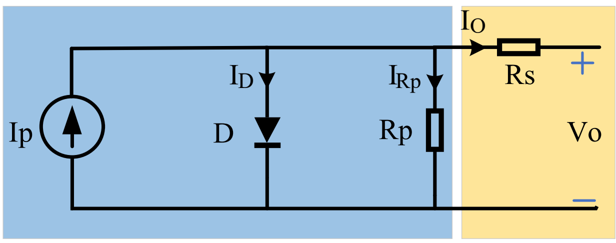

Figure 5. PV panel equivalent circuit

In the study of [15], and [35] the below formulas is obtained.

$$I_o = I_p - I_D - I_{R_p} \quad (13)$$

$$V_o = V_D - I_o * R_s \quad (14)$$

$$V_D = V_o + I_o * R_s \quad (15)$$

$$I_{out} = I_{Photo} - I_{sat} * \left(e^{\frac{V_{out}+I_{out}*R_{series}}{n_{cell}*V_{thermal}}} - 1 \right) - \frac{V_{out}+I_{out}*R_{series}}{R_{par}} \quad (16)$$

B. TEG Device

TEG Device use temperature difference between two surfaces that produce electrical energy. The TEG device use Seebeck effect, Peltier effect, and Thomson effect and Joule Heating Principles for producing electrical energy [36]. The equivalent circuit of the TEG devices shown in Fig. 6.

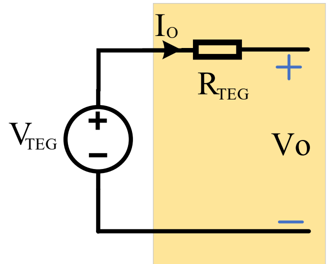

Figure 6. TEG device equivalent circuit

From the article of [16], [18-21], [35],

$$V_{TEG} = \alpha * \Delta T \quad (17)$$

If there are more than 1 TEG in the system, the Eq.17 becomes,

$$V_{TEG} = \alpha * \Delta T * n_{TEG} \quad (18)$$

$$V_{out} = V_{TEG} - R_{TEG} * I_{out} \quad (19)$$

$$I_{out} = \frac{V_{TEG}}{R_{TEG} + \frac{V_{out}}{I_{out}}} \quad (20)$$

$$R_{out} = \frac{V_{out}}{I_{out}} \quad (21)$$

For finding maximum voltage and current. If $0 \le R_{out} < \infty$

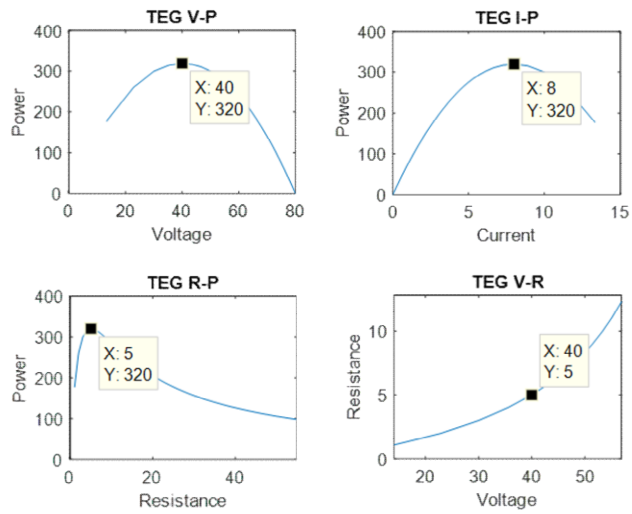

Figure 7. Maximum Power Point Voltage-Current and Resistance of TEG

For the used TEG, voltage and current values, resistance value can be obtained with these equations.

$$V_{mppt} = \frac{V_{oc}}{2} \quad (21)$$

$$I_{mppt} = \frac{I_{short}}{2} \quad (22)$$

The result similar to the [19],

$$R_{TEG} = \frac{V_{mppt}}{I_{mppt}} = \frac{40}{8} = 5\ ohm \quad (23)$$

$$R_{mppt} = R_{TEG} = 5\ ohm \quad (24)$$

V. Fuzzy Logic based MPPT

Fuzzy Logic is an artificial intelligent control technique that has three different important parts called as fuzzifier, interference system, and defuzzifier. Firstly, input variables of the controller are applied to fuzzifier system. In this part, the variables are converted to the fuzzy variables and the values according to used system. The obtained variable or variables feed the interference system which contains the fuzzy logic rules. The results of the inference system are converted with defuzzifier part and it is ready to use for controlling the system. In the system, the fuzzifier and defuzzifier are designed to determine some coordinates. After the interference system, these coordinates are very important for obtaining the result [26],[29], [31-34].

In this study, FL control system is used to obtain MPPT for renewable energy sources. The designed FL MPPT controller has 2 inputs and 1 output. The input membership and output membership functions are shown in Fig.8, Fig.9 and Fig.10.

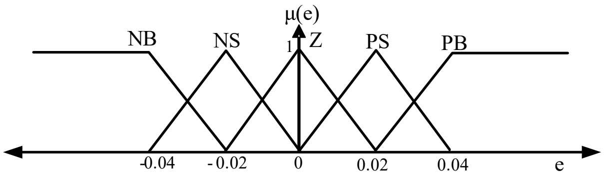

Figure 8. Input e membership function

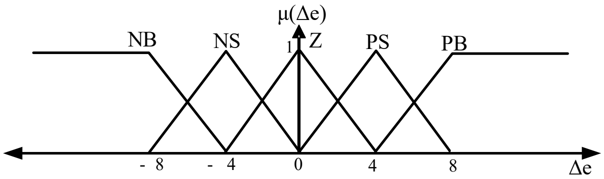

Figure 9. Input Δe membership function

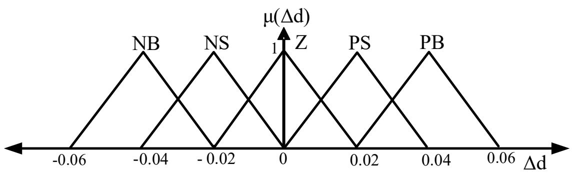

Figure 10. Output Δd membership function

There are two inputs and one output of FL MPPT controller. The inputs are error (e) and change of error (Δe) are given in Eq.25.

$$e = \frac{\Delta P}{\Delta V}, \;\; \Delta_e = \frac{\Delta P\,(t) - \Delta P\,(t-1)}{\Delta V(t) - \Delta V\,(t-1)} \qquad (25)$$

And additional to fuzzy system the anti-wind up is adapted to get d (duty value) from Δd.

ΔE \ E	NB	NS	Z	PS	PB
NB	Z	Z	PS	NS	NB
NS	Z	Z	Z	NS	NB
Z	PB	PS	Z	NS	NB
PS	PB	PS	Z	Z	Z
PB	PB	PS	NS	Z	Z

Figure 11. The FL MPPT rule base

In the rule base table, NB: Negative Big, NS: Negative Small, Z: Zero, PS: Positive Small, PB: Positive Big. The model of proposed FL based MPPT is simulated with MATLAB/Simulink as shown in Fig.12.

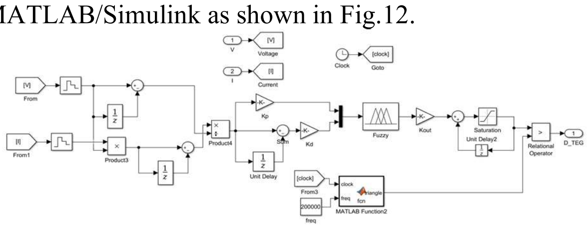

Figure 12. The model of FL based MPPT

VI. Design and Simulation of Proposed System

There are two different renewable energy sources (PV and TEG) used in the proposed system. The obtained voltages from these sources are converted different levels by using boost converter. Also, this converter is switched by using FL based MPPT control. The DC power is converted AC power via Full Bridge Inverter Topology with Sinusoidal Pulse With Modulation control. The simulation of all the proposed system is shown in Fig.13.

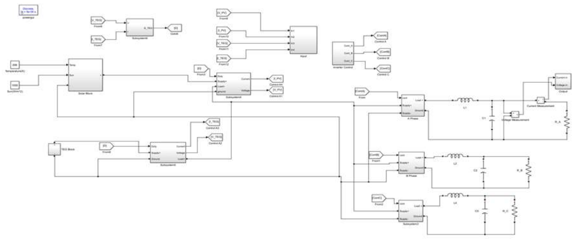

Figure 13. PV & TEG hybrid system with full bridge inverter

The parameters of PV, TEG, boost converter and FL based MPPT control are given in Table 1.

Table 1. The parameters of proposed system

Parameter	Value
PV Panel Parameters	
Parameter	**Value**
Open Circuit Voltage	192V
Voltage at MPPT	160V
Temperature coefficient of V_{oc}	-0.35%
Short Circuit Current	18A
Current at MPPT	16A
Temperature coefficient of I_{short}	0.1%
Cell number each Module	320
Saturation Current	$4.4644 * 10^{-10}$
Diode's ideality factor	0.95955
Parallel Resistance	129.0835Ω
Series Resistance	0.48525 Ω
TEG Parameters	
Open Circuit Voltage	80V
Voltage at MPPT	40V
Delta Temperature	50 ºK
Alpha Value	0.2
TEG Device each module	8
Short Circuit Current	16A
Current at MPPT	8A
Source Parameters of Design	
PV Voltage at MPPT	320V
PV Current at MPPT	16A
TEG Voltage at MPPT	320V
TEG Current at MPPT	16A
Boost Converter Parameters	
Inductance Value	0.0015H
Capacitance Value	$5 * 10^{-5}$ F
Needed Load for each source	80Ω
Fuzzy Logic based MPPT Parameters	
Gain of error (e)	0.02
Gain of Δe	100
Output gain of fuzzy	5020
Switching Frequency	10 kHz

VII. Results

Simulations of a standalone system with AC load fed from two renewable energy sources such as PV and TEG are performed using MATLAB/Simulink. The obtained voltages and currents from PV and TEG are shown in Fig.14 and Fig.15, respectively. Also, behaviors of PV and TEG sources are shown in Fig.16. RMS value of phase A voltage, phase A voltage, RMS value of phase A current and power are given in Fig.17, Fig.18, Fig.19 and Fig.20. If the input and output powers are compared, the efficiency is obtained as 98.8%.

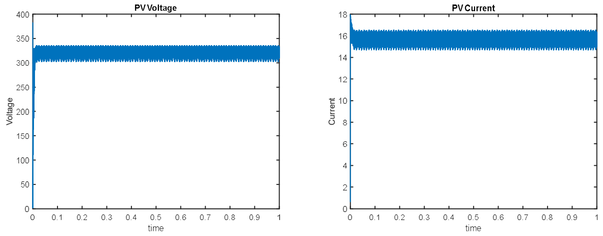

Figure14. PV voltage and current

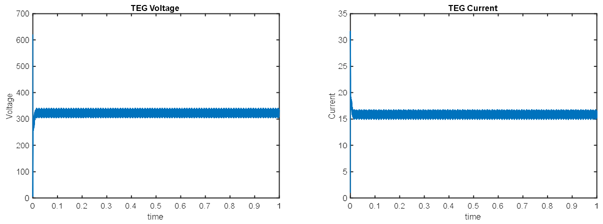

Figure 15. TEG voltage and current

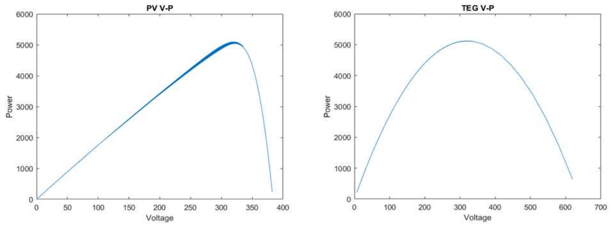

Figure 16. PV and TEG Behavior

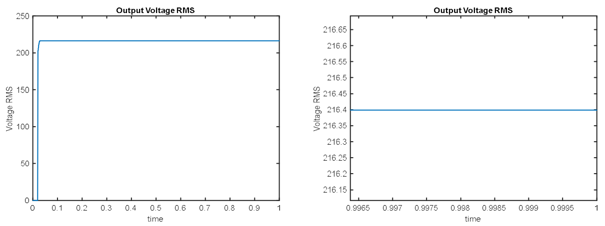

Figure 17. RMS value of phase A voltage

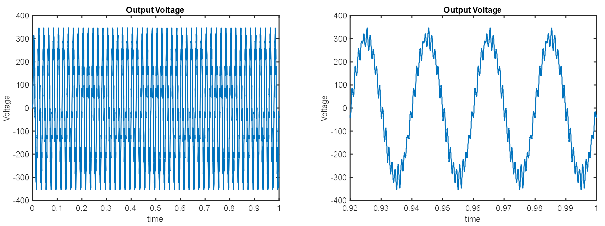

Figure 18. Phase A voltage

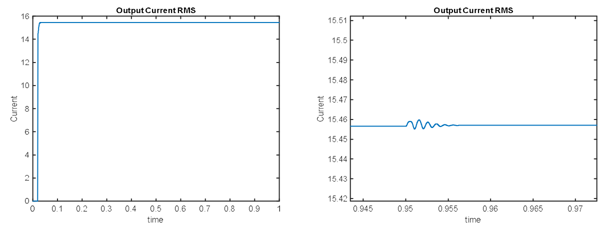

Figure 19. RMS value of phase A current

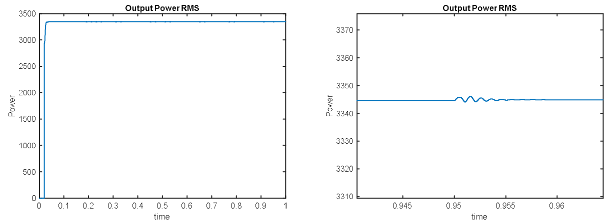

Figure 20. Phase A power

VIII. Conclusion

In the paper, PV- TEG hybrid system which is controlled by Fuzzy Logic Control for MPPT fed AC loads via full bridge inverters. The DC level of renewable energy sources are converted to different levels by boost converters. Two system is connected to the 3 different full bridge inverter which has 120° phase difference. The aim is to obtain high efficiency (greater than 95%) with this system and the efficiency is 98.8%.

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