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PV/Diesel Hybrid System for Fuel Production from Waste Plastics Recycling

Faten Hosney Fahmy[1], Ninet Mohamed Ahmed[2], Hanaa Mohamed Farghally[3],
Photovoltaic Department, Electronics Research Institute, Giza, Egypt.

Abstract: *The treatment of wastes has become one of the most important concerns of modern society. Converting waste plastic into gasoline and diesel fuel through a highly effective low-cost pyrolysis process is a promising technology. In this paper PV/Diesel/Battery hybrid system is suggested to fulfill the load demand of waste plastic recycling pyrolysis process. A Mathematical and simulation models using MATLAB/ SIMULINK software for the hybrid PV/Diesel/Battery system components have been developed. Also, this paper presents a control strategy using Artificial Neural Network Controller (NNC) technique for coordinating the power flow among the different components of the PV/Diesel/Battery hybrid system. The results indicate that the proposed control unit using NNC can be successfully used for controlling the power system for the waste plastic recycling pyrolysis process.*

Keywords- *Battery, Diesel generator, Matlab/Simulink, NNC, Photovoltaic, Waste plastic recycling.*

I. Introduction

Increased population growth and economic development are accelerating the rate at which energy, and in particular electrical energy is being demanded. The use of fossil fuels is now widely accepted as unsustainable due to depleting resources and the subsequent increase in price and the accumulation of greenhouse gases in the environment that have already exceeded. All methods of electricity generation have consequences for the environment, so meeting this growth in demand, while safeguarding the environment poses a growing challenge [1-3]. After food waste and paper waste, waste plastic is the major constitute of municipal and industrial waste in cities. The global production of plastics has seen an increase from around 1.3 million tons in 1950 to 245 MT in 2006 [4]. Worldwide consumption of plastic is expected to touch 297 million tons by 2015. Hence, waste plastics pose a very serious environmental challenge because of their huge quantity and disposal problem as thermoplastics do not biodegrade for a very long time. Thus mankind has to rely on the alternate/renewable energy sources like biomass, hydropower, geothermal energy, wind energy, solar energy, nuclear energy, etc. [5]. Among all the renewable energy resources the solar and wind energies have the great potential as a power generating energy source, because of their many advantage like low or zero emission of pollutant gases, low cost, inexhaustible sources and easy availability of these energy sources [6 -7]. In addition to, waste plastic to liquid fuel is also an alternate energy source path, which can contribute to depletion of fossil fuel as in this process. Pyrolysis process appears to be a technique that is able to reduce a bulky, high polluting industrial waste, while producing energy and/or valuable chemical compounds. Liquid fuel with similar fuel properties as that of petro fuels is obtained [4].

Hybrid renewable energy sources can ensure sustainable, efficient utilization and electric AC-DC supply_security [8]. It can raise power supply reliability and reduce the system cost according to local environmental condition and load characteristics. The choice of renewable power options is partly determined by the region in which the facility is located [9 -10].

One of the most promising renewable energy technologies is photovoltaic (PV) technology since it offers many advantages such as incurring no fuel costs, not being polluting, requiring little maintenance , and emitting no noise, The performance of the PV system depends upon several factors, especially the meteorological conditions such as solar radiation, ambient temperature and wind speed [11].

The use of diesel generators to ensure continuous power supply has the disadvantage of increasing the greenhouse gas emission which has a negative impact on the environment. Incorporating battery storage and a renewable energy source, to form a hybrid power supply system, can alleviate most of the problems mentioned for the diesel-only power system. The combinations of PV locally available solar energy systems with the continuously available diesel power plants is being disseminated worldwide to reduce diesel fuel consumption and to minimize atmospheric pollution [12-14].

Utilization of renewable energy sources for producing liquid fuel from recycling of waste plastics by a cost effective pyrolysis method will contribute on both solving the problem of plastic disposal to a great extent and consequently solving the environment problem. In addition to, adding one source of energy [4].

This paper presents the use of PV/Diesel/Battery hybrid energy system for supplying the electrical power to meet the load requirement for household waste plastics recycling system for liquid fuel production. A simulation of hybrid PV/Diesel/Battery system using MATLAB/ SIMULINK software has been performed. The simulation has been done to assure that the PV/Diesel/Battery system is suitable for recycling process operation. Artificial Neural Network Controller (NNC) model was developed to simulate the performance of PV/Diesel/Battery power system.

II. Location

Cairo is chosen as the site under consideration. The specific geographical location of Cairo city is at a location of 30° 05' N latitude, 31° 17' E longitude and elevation 34.4 m with annual average solar radiation of 5.21 kWh/m²/d and clearness index of 0.597. Solar radiation, ambient temperature and the specific geographical location data for this city were obtained from Egyptian solar radiation atlas [15].

III. PV/Diesel/Battery Waste Plastic Recycling System Description

Figure1 illustrates the proposed PV/Diesel/Battery waste recycling system. It contains power sources which are PV array, diesel generator engine system, storage battery bank, inverter, NN controller unit and AC load (M_1, M2, M3, P1, P2, P3 and pyrolysis reactor).

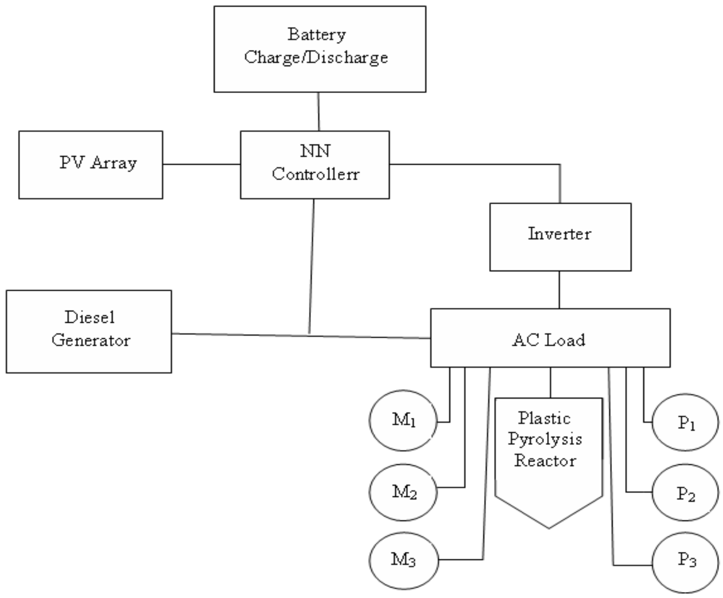


Fig.1 The proposed PV/Diesel/Battery waste recycling system configuration

IV. Load Estimation

Table I illustrates the main electrical equipments for waste plastic recycling system. The waste recycling system is assumed to operate for 10 hours from 8:00 to 18:00 o'clock with a peak load of 21.5 kW in addition to 1 hour before 8:00 o'clock and 1 hour after 18:00 o'clock of 1 kW for preparation and closing as shown in Fig. 2. The electrical daily load curve during two days in the year, one in winter and the other in summer is the same since the electrical load is the same for summer and winter seasons. Figure 2 illustrates the hourly daily electrical load of the waste recycling system. This figure indicates that, the peak load occurs during the period between 12:00 and 16:00 o'clock.

Table I: The hourly load demand for household waste plastic recycling system

Symbol	Equipment	Power (KW)
M1	Crusher motor	2.5
M2	Feeder motor	2.5
M3	Reactor motor	1.5
P1	Receiver tank pump motor	1.5
P2	Storage tank pump motor	1.5
P3	Heavy oil tank pump motor	1.5
I H	Waste plastic recycling induction heater	15

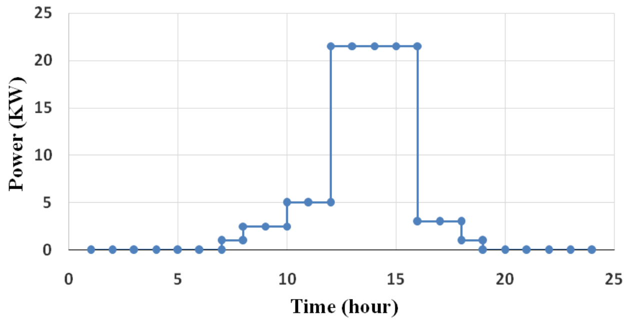
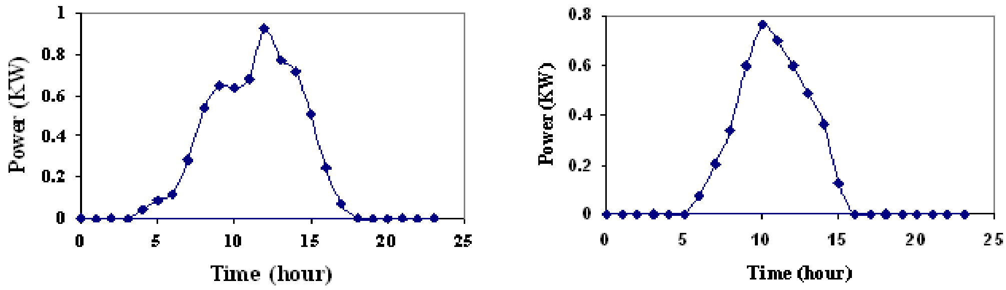


Fig.2 Electrical hourly load curve of waste plastic recycling system

V. Weather Data

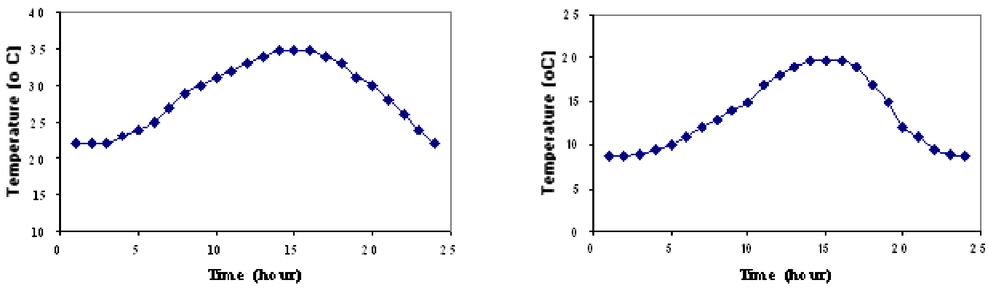
The inputs to PV system are the solar radiation and the air temperature. Figure 3 shows the hourly solar irradiance data for Cairo city which is collected for a typical summer and winter days. By comparing the winter & summer solar data which is shown in Fig. 3, it is noticed that the time frame when solar energy is available (the solar insolation duration) is wider in the summer than in the winter. Also, for a typical summer day, the peak radiation of about 926 W/m^2 is estimated, while for a typical winter day a peak of about 780 W/m^2 is estimated.



Summer Winter

Fig.3 Global solar irradiance of Cairo city for a typical two days in summer and winter

Figure 4 shows the hourly air temperature of Cairo city for a typical two days in winter and summer. It is observed that, the air temperature in summer season is much higher than that in winter.



Summer Winter

Fig. 4 Air temperature of Cairo city for a typical two days in summer and winter

VI. Commercial Waste Pyrolysis System

The waste plastic pyrolysis process to produce oil for using as liquid fuel or chemical feedstock is common at the commercial scale in Japan. At the small scale, there are many companies manufacturing 1 ton /day batch pyrolysis units, using plastics derived from household waste. For example, the MCC Yukaki Ltd. company in Japan operates a plastic pyrolysis plant that typically processes one tone per day of plastics, producing medium and light oil is shown in Fig.5 [16-18].The oil is combusted to provide the energy requirements of the pyrolysis system and exported for combustion to raise steam for both thermal and electrical power generation.

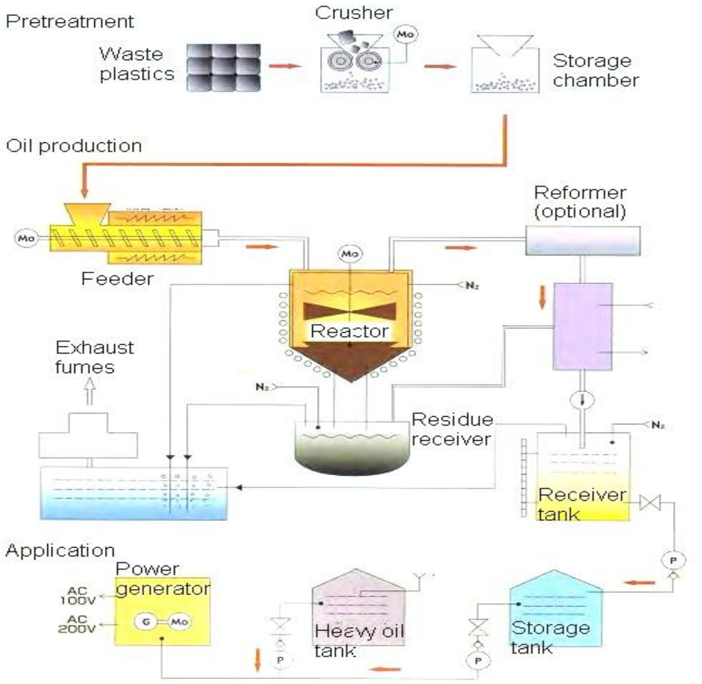


Fig.5 Schematic diagram of the MCC Yukaki Ltd. 1 ton per day plastics pyrolysis system

The process of conversion waste plastic to liquid fuel consists of three main stages; pretreatment, generation and application which is indicated in Fig.5 and can be described as follow:

***Pretreatment stage*:** The pretreatment stage includes sorting for the removal of unsuitable materials from incoming waste plastic, crushing and storing the crushed plastic in the storage chamber.

***Generation stage*:** The generation process takes place in a stainless steel cylindrical reactor with an opening at each end of its upper section: one opening for raw material feeding and the other for waste removal. It is operated in ambient pressure at temperatures lower than 500 degrees Celsius. There are also different types of reactors and heating equipment. Both kiln-type and screw-type reactors have been proposed, while induction heating by electric power has been developed as an alternative to using a burner. The output of the reactor is stored in the reservoir tank and the residue outs from the bottom of the reactor to the residue receiver.
Application stage: In this stage the generated oil is pumped to the storage tank from which it also pumped to the heavy oil tank and to the power generation unit.

VII. Hybrid System Components

7.1 Photovoltaic Array

Photovoltaic (PV) Solar energy is used as the base-load power source. PV array size is dependent on the load profile, solar radiation, and renewable fraction. The PV modules used were Polycrystalline silicon with 130W Maximum Power. The details of solar module properties are shown in Table II [19].

Table II: Specifications of PV module

Parameter	Value
Maximum power (P_{max})	130 Wp
Open circuit voltage (V_{oc})	21.5 V
Maximum power point voltage(V_{mpp})	17.4 V
Short circuit current (I_{sc})	7.99 A
Maximum power point current (I_{mpp})	7.49 A

7.2 Diesel Generator (DG)

Diesel generator (DG) technology is widespread and the development of the power plant is relatively easy. A diesel generator is in service at times when the PV array fails to meet the load. Due to few inherent advantages of diesel generator listed below, it is used as a backup source of power generation [20-21].

a) It attains full load operating condition very quickly.
b) Highly qualified people are not required to operate this generator because of simplicity of application.
c) In a few seconds it can be started and it can gain rated speed.
d) Under varying load condition stability is maintained.
e) Installation requires smaller place compare to other generating systems.

Diesel generator is a combination of a diesel engine with an electric generator (alternator) to generate electrical energy. The diesel generator comprises a speed governor, a diesel engine, an excitation system and a synchronous generator.

The governor and the diesel engine system control the generator speed and provide mechanical power to the generator. A speed regulator and an actuator are the main components of this system. A 25 kW KOBOTA diesel generator is chosen in this study.

7.3 Battery

Battery is used as a storage device which has two operation modes: charging and discharging. Excess electricity from PV and diesel can be stored in the battery. The purpose of the battery is to alleviate the mismatch between the load demand and electricity generation. The storage batteries are a key factor in a hybrid system of renewable energy; it allows to minimize the number of starting/stopping cycle of the diesel generator which reduces the problem of its premature wear, and to satisfy the request of the load in spite of solar source fluctuations.

The battery type chosen is Trojan Battery. It is a 6 volt, 225 AH Flooded Lead Acid Battery T-105, which is perfectly suited for use in renewable energy systems where lowest life-cycle cost is the key consideration [22].

7.4 Inverter

The inverter is used to interface the DC voltage to the consumer load AC requirements. The PV arrays produce direct current (DC) at a voltage that depends on the design and the solar radiation. The DC power then runs to an inverter, which converts it into AC voltage. The inverter size is rated based on the selected PV size, in order to maximize the quantity of energy which is harvested from the PV arrays. A 25 KW inverter is used in this study.

VIII. Power System Mathematical Model

The development of the mathematical model of the hybrid power system sources which are used for supplying the electrical system of waste plastic recycling process is described in this section.

8.1 Modeling of Diesel Engine

The diesel engine is a combination of an internal combustion (IC) engine and governor. The governor comprises speed controller and actuator. The governor of a diesel engine maintains the constant speed throughout the operation of diesel engine. The regulator and the actuator transfer functions can be expressed by Eq. (1) and Eq. (2) as follow [21]:

$$H_r = \frac{k_r(1+T_{ra}s)}{(1+T_{r1}s+T_{r2}s^2)} \qquad (1)$$

$$H_a = \frac{(1+T_{a1}s)}{s(1+T_{a2}s)+(1+T_{a3}s)} \qquad (2)$$

Where, k_r is the regulator gain, T_{r1}, T_{r2} *and* T_{r3} are the regulator time constants, T_{a1}, T_{a2} *and* T_{a3} are the actuator time constants. The differential equations describing the diesel engine and speed regulation are given by Eq. (3) and Eq. (4) [21]:

$$\frac{dP_c}{dt} = -\frac{k_1}{\omega_{ref}} \Delta\omega \qquad (3)$$

$$\frac{dm_B}{dt} = \frac{1}{\tau_2}(k_2 P_C - \frac{k_2}{\omega_{ref} R} \Delta\omega - m_B) \qquad (4)$$

Where,
P_c is the compression ratio*;* m_B is the diesel engine fuel consumption rate (kg/sec),
K_1 is the governor summing loop amplification factor,
R is the diesel engine permanent speed droop,
ω_{ref} is the reference speed of engine in rad/sec,
The engine is represented by a gain K_2 and a dead time τ_2,
The dead time can be expressed as [21]:

$$\tau_2 = \frac{60 s_t}{2Nn} + \frac{60}{4N} \qquad (5)$$

Where, s_t =4 for four stroke engine, N is the speed in rpm, and n is the number of cylinders.
The mechanical power (P_m) output produced as a result of combustion is [21]:

$$P_m = C_1 m_B \eta \qquad (6)$$

Where, C_1 is proportionality constant, η is the efficiency. The numerical values of these constant parameters are listed in Table III [21].

Table III: Values of constant parameters of the diesel model

Constants Parameter	**Numeric values**
T_{r1}, T_{r2} and T_{r3}	0.01, 0.001 and 0.2
T_{a1}, T_{a2} and T_{a3}	0.25, 0.009 and 0.0384
K_r	40
Engine Time Delay	0.24

8.2 Modeling of PV Array

PV array consists of many modules connected in series and parallel to provide the desired output terminal voltage, current and power. The output current (I) from the PV cell is found by applying the Kirchhoff's current law (KCL) [3].

$$I - I_{SC} - I_d \qquad (7)$$

Where, I_{sc} is the short-circuit current that is equal to the photon generated current, and I_d is the current shunted through the intrinsic diode. The diode current I_d is given by the Shockley's diode equation [3]:

$$I_d = I_o(e^{\frac{qV}{kT}} - 1) \qquad (8)$$

Where: I_o is the reverse saturation current of diode (A), q is the electron charge (1.602×10^{-19} C), V is the voltage across the diode (V), k is the Boltzmann's constant (1.381×10^{-23} J/K), T is the junction temperature in Kelvin (K). Replacing I_d of Eq. (7) by Eq. (8) gives the current-voltage relationship of the PV cell.

$$I = I_{SC} - I_o(e^{\frac{qV}{kT}} - 1) \qquad (9)$$

The reverse saturation current of diode (I_o) is constant under the constant temperature and found by setting the open circuit condition. Using Eq. (9) let I = 0 (no output current) and solve for I_o.

$$0 = I_{SC} - I_o(e^{\frac{qV}{kT}} - 1) \tag{10}$$

$$I_{SC} = I_o(^{\frac{qV}{kT}} - 1) \tag{11}$$

8.3 Battery Model

The battery model describing the relationship between the voltage, current and the state of charge can be found in [23]. The terminal voltage of a battery can be expressed in terms of its open circuit voltage and the voltage drop across the internal resistance of the battery as given in the following equation [23]:

$$V_B = E_{oc} + I_B R_B \tag{12}$$

Where V_B is battery terminal voltage (V), E_{OC} is battery open circuit voltage (V), I_B is battery current (A) (positive when charging and negative when discharging), R_B is internal resistance of the battery (ohms). The open circuit voltage, E_{OC}, is expressed as a logarithmic function of the state of charge of the battery using the flowing formula [23]:

$$E_{oc} = VF + b\log(SOC) \tag{13}$$

Where *VF* is a full charge rest voltage (V), b is an empirical constant, and *SOC* is battery state of charge. The battery state of charge is the instantaneous ratio of the actual amount of charge stored in the battery and the total charge capacity of the battery at a certain battery current. In the model, it is estimated as [23]:

$$SOC = SOC_0 + \left(\frac{Q}{BC}\right) \tag{14}$$

Where SOC_0 is the previous *SOC*, *Q* is amount of exchanged charge from the previous time to the time of interest (C), and *BC* is battery capacity (C). The exchanged charge, *Q*, in Eq. (14) can be determined by summing up the charge flowing over the period of interest which is expressed as [23]:

$$Q = \int_0^t I_B dt \tag{15}$$

Where I_B is battery current (A), the value of I_B can be positive or negative depending on whether the battery is charging or discharging. The positive or negative value therefore represents the direction of the charge that flows into or out of the battery, respectively. The variation of the internal resistance of battery, R_B, is mainly due to two components; namely, the resistance of the electrode, $R_{electrode}$, and the resistance of the electrolyte, $R_{electrolyte}$ as indicated by the following equation [23]:

$$R_B = R_{electrode} + R_{electrolyte} \tag{16}$$

$R_{electrode}$ and $R_{electrolyte}$ are a function of *SOC*, which can be expressed as:

$$R_{electrode} = r_1 + r_2(SOC) \tag{17}$$

$$R_{electrolyte} = [r_3 - -r_4(SOC)]^{-1} \tag{18}$$

Where, r_1, r_2, r_3 and r_4 are empirical constants. It is noted that as these constants have different values for charging and discharging modes, the values of $R_{electrode}$ and $R_{electrolyte}$ are therefore different in those modes as well. Table IV indicates the values of various parameters for the battery model in this study.

Table IV: Values of various parameters for the battery model in this study [23]

Parameter	Charging Mode	Discharging Mode
For open circuit voltage (E_{oc})		
VF	*13.250V*	*12.662V*
B	*0.810*	*0.724*
For internal resistance (R_B)	*0.062 ohms*	*0.055 ohms*
r_1	*0.046 ohms*	*–0.010 ohms*
r_2	*95.638 ohms^{-1}*	*4.270 ohms^{-1}*
r_3	*52.671 ohms^{-1}*	*–100.730 ohms^{-1}*
r_4		

IX. System Controller

Artificial intelligence (AI) techniques are becoming useful as alternate approaches to conventional techniques or as components of integrated systems. They have been used to solve complicated practical problems in various areas and are becoming more and more popular nowadays. Neural Network controller (NNC) is a computational structure where many simple computational elements, called artificial neurons, perform a nonlinear function of their inputs. Such computational units are massively interconnected and are able to model a system by means of a training algorithm. This algorithm attempts to minimize an error measure that is computed in different ways depending on the specific technique used to adjust the connections (i.e., the learning algorithm) [24].

Neural networks have the potential to provide some of the human characteristics of problem solving that are difficult to simulate using the logical, analytical techniques of expert system or standard software technologies. A control system, which includes the NNC, is developed for achieving the coordination between the components of a PV/Diesel/Battery hybrid system as well as control the energy flow.

The purpose of the controller in this work is to ensure that the demand is supplied at all times. The control unit controls the system under weather fluctuation conditions by comparing the summation of PV generator power, diesel generated power and battery power with the reference load power. The difference between them is the error of power which is fed as input to the controller which attempts to reduce the difference between the actual power and the reference load power.

The developed NNC which is shown in Fig. 6 is employed a 2-neuron input layer, an 8-neuron hidden layer and 1-neuron output layer. The input parameters to the NNC are; the reference load power (P_{Lref}) and the error signal (difference between the reference load power and the total output generated power). The output of the NNC is the variation of the battery power $\Delta P_{Battery}$.

Control Strategy of the System

A power management controller is designed for the system to coordinate the power flows among the different power sources. The block diagram of the PV/ Diesel/ Battery hybrid energy system with the associated NNC is shown in Fig.7. During the operation of the hybrid PV/ Diesel/ Battery system, different situations may appear: The input to the controller is the reference load power and the error signal (E) which is the difference between the reference load power (P_{Lref}) and the total system power (P_{PV}, P_{DG}, P_B). The suggested power management strategy can be described by the following three situations shown in Table V.

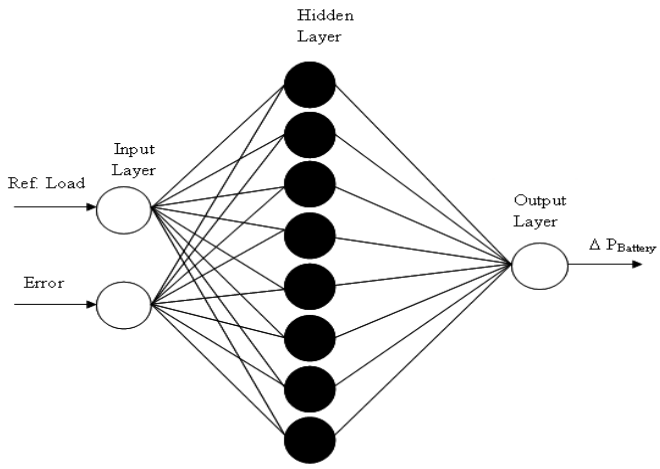


Fig. 6 NNC architecture used for controlling the operation of the PV/ Diesel/Battery system

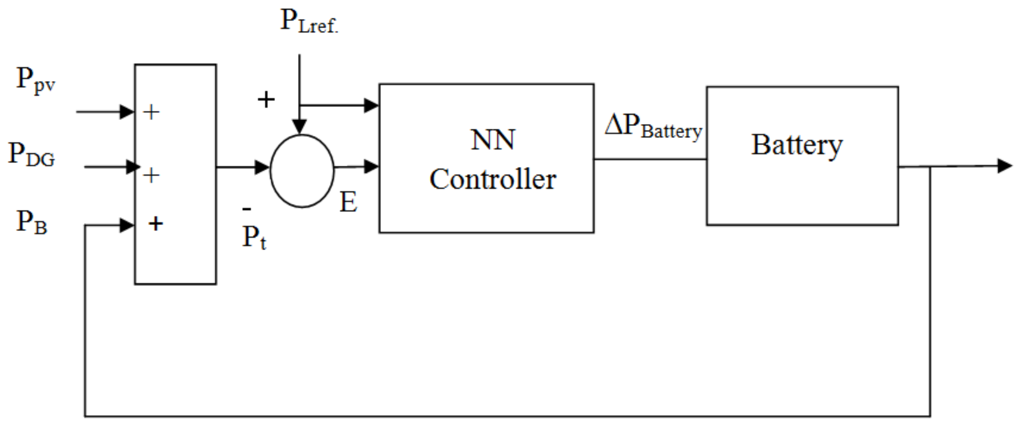


Fig.**7** The block diagram of the PV/ Diesel / Battery power system with NNC

Table V**:** Different situations of controller action for the PV /Diesel/Battery system

Situation	Power Situation	Controller Action
1	$P_t > P_L$	The controller puts the battery in charge condition. When the battery capacity reaches a maximum value, the control system stops the charging process.
2	$P_t < P_L$	The controller puts the battery in the discharge condition. If the battery capacity decreases to its minimum level, C_{batmin}, the control system disconnects the load.
3	$P_t = P_L$	The storage capacity remains unchanged.

X. System Simulation

In this section, the SIMULINK model of hybrid power system based on PV array and diesel generator set is briefly described. MATLAB/ SIMULINK software is used to model the proposed hybrid system. Figure 8 shows the MATLAB/ SIMULINK diagram of the hybrid power system. The system consists of a number of units which are PV array, diesel generator, storage battery bank, load and NNC unit.

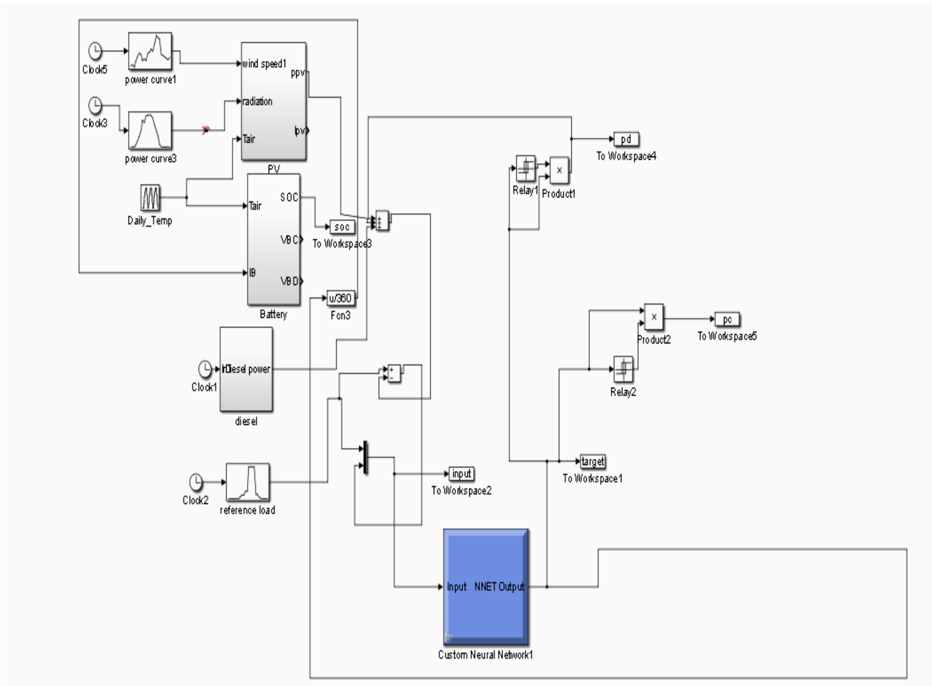


Fig. 8 MATLAB/ SIMULINK block diagram of the PV/ Diesel/Battery with NNC

XI. Result and Discussion

In this section the performance of the PV/ Diesel/Battery power system is evaluated and compared, for two different days (one day in winter and the other in summer). The simulation results of PV/ Diesel /Battery system are reported to verify the effectiveness of the proposed controller under variable weather conditions. Although, the PV generator is the base power source, supplying its maximum output depending on solar radiation levels, the diesel generator and battery bank contribution depending on the load demand.

The power generation of the hybrid power system components such as PV generated power, diesel power and battery power for a typical two days in summer and winter are investigated**.** Figure 9 shows the typical power profile generated by a PV generator for two days in the year, one in winter and the other in summer. A PV generator offers power production during the day's hours between 3:00-18:30 o'clock in summer day, and during winter day between 5:00-15:30 o'clock. The variations of PV output power have the same tendency as the solar insolation.

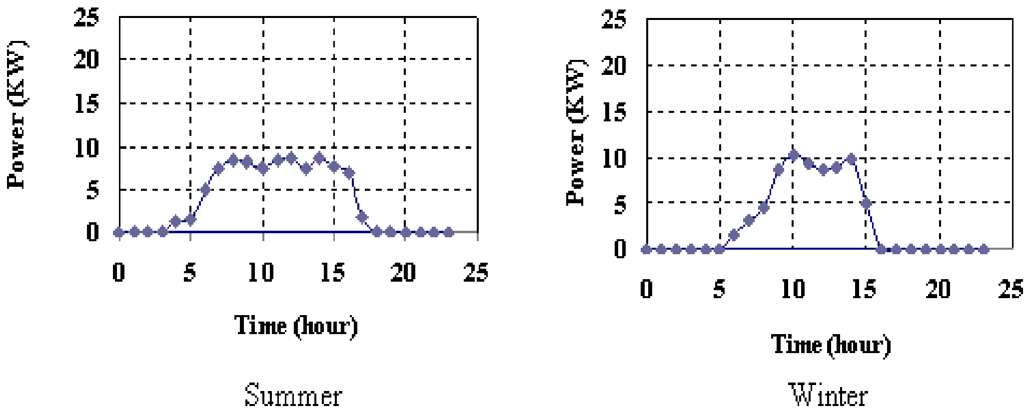


Fig.9 The l power profile generated by a PV generator for two days

Figure 10 shows the typical power profile generated by a diesel generator in two days in the year, one in summer and another in winter. The diesel generator is shown to operate only to supply the deficit in peak load power in conjunction with the battery bank. It is observed that, the diesel generated power in winter is larger than that produced in summer.

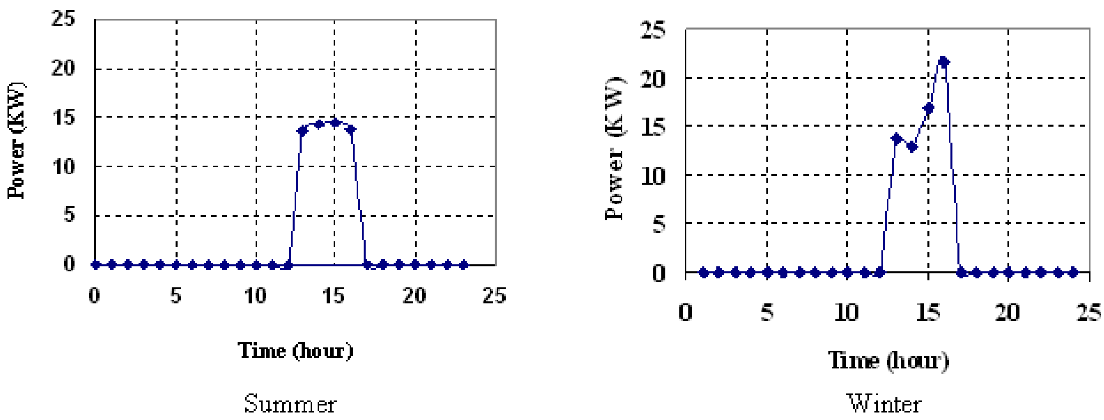
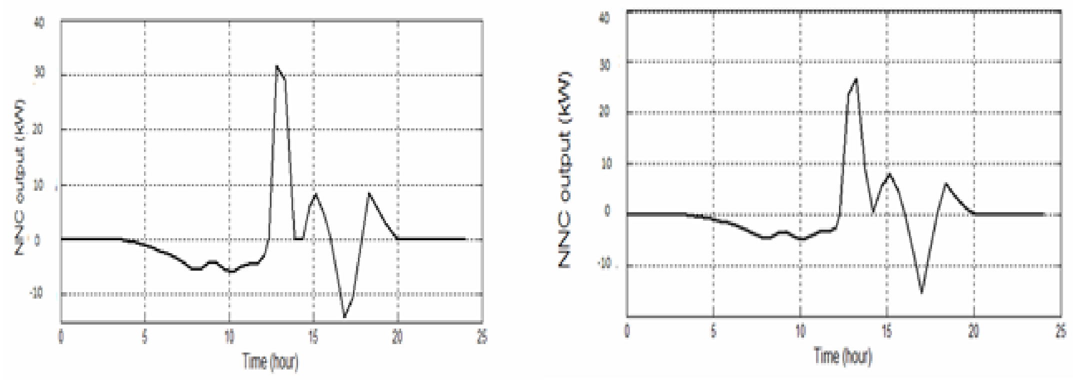


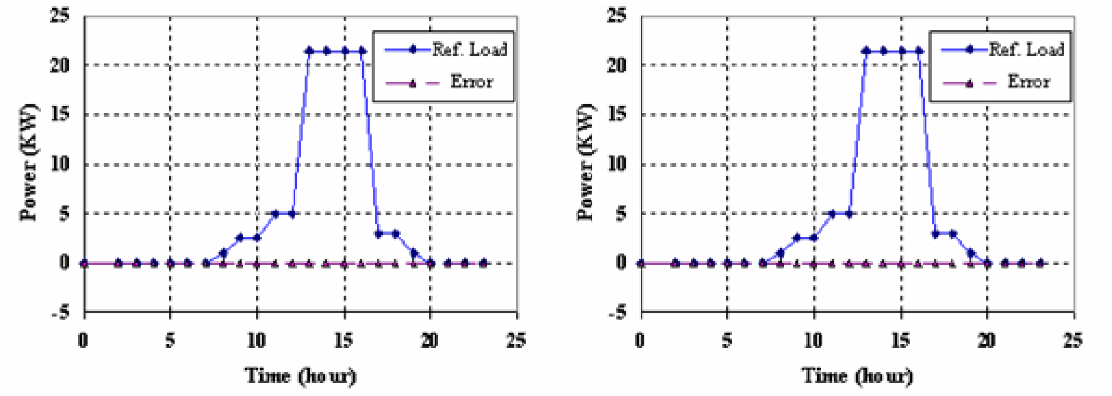
Fig.10 The power profile generated by a diesel generator in two days

The power profile of battery in two days in the year, one in winter and the other in summer is indicated in Fig. 11. When the generated electrical power from both the PV and diesel generator is greater than the power needed by the load, the energy surplus is stored in the battery and the battery is in charge state and the battery power is positive. So it could be clear from Fig. 11 that, when the generated power is more than the required load power, the controller is able to charge the battery bank, and when the required load power is more than generated power of the hybrid system then the controller is able to discharge the battery bank. Power from the battery bank changes (discharge/charge) to maintain the power stability of the system. Figure 12 indicates the NNC output through 24 hours, the error resulting with NNC is approximately zero during the whole day. Thus, it is clear that whatever the day is in summer or in winter the load is completely covered, and this is achieved by adjusting the battery and/or the diesel to supply the complementary power when there is a deficit on the PV power noitareneg, which is shown to be variable according to the incident solar insolation level for the summer and winter days.



Summer Winter

Fig. 11 The power profile of battery in two days in the year



Summer Winter

Fig. 12 NNC output through 24 hours in two days in the year

XII. Conclusion

In this paper, a hybrid PV/Diesel/Battery system with appropriate power flow controller was designed and modeled for powering the waste plastic recycling process. A simulation of hybrid PV/Diesel/Battery system using MATLAB/ SIMULINK software was performed. Artificial Neural Network Controller model was developed to simulate the performance of PV/Diesel/Battery power system. The simulation results showed that the performance of the suggested hybrid power system is satisfactory under transient solar and load power conditions. Also the developed NNC can successfully regulate the power flow through the system components and the load. The produced liquid fuel from the waste plastic recycling process is considered as a source of power which can be used as a fuel for the diesel generator power source.

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