Mini Renewable Hybrid Distributed Power Plants for Lebanon

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Abstract

Lebanon has spent billions of dollars on its electricity sector, but the demand is higher than available power. In peak demand time, blackouts are the major phenomena in almost all the Lebanese regions. As the world today is going into green energy, this project lunches the idea of implementing hybrid-renewable distributed energy systems in Lebanon either by individuals or by government. This step will minimize green house gas emissions, increase the reliability of the grid, save in the individual's electricity bill and finally, increase the power generation capacity in Lebanon. For all the mentioned problems, distributed generation using hybrid-renewable energy systems is proposed as a future solution for the Lebanese energy sector. Losses in the transmission and distribution system will be reduced since power is generated near loads. The grid availability and stability will increase and individuals can save money in their electricity bill and finally the generated power is clean and nonpolluting. A study of a design will be launched, including simulation using MATLAB/SIMULINK.

Keywords: Smart Grid; Distributed; Renewable; MPP; Photovoltaic; Boost Converter; Inverter; Hybrid; Power flow

1. Introduction

Lebanon is a small country in the Middle East located east of the White Mediterranean Sea. Most of the power is generated using imported petroleum products and an amount of $500 million is the price of yearly imported fuel for electricity production. Despite this huge amount of money, the power demand exceeds the generation capacity and in peak demand time, blackouts are the common problems [1]. Losses in the transmission system and grid are very high and are mainly due to technical problems and theft (illegal connections on the grid). For example in 1997 the total grid losses were approximated to 52%, from which 15% were due to technical problems [1]. The energy sector is also responsible for most of the green house gas emissions. An inventory done in 1994 about gas emissions showed that 85% of CO_2 and 96% of SO_2 emissions were due to the energy sector [2]. Table 1 shows that Lebanon will remain at a power deficit in year 2015.

Table 1. Future Power Capacity [1]

YEAR	2015
EXPECTED INSTALLED CAPACITY (MW)	4148
EXPECTED CONSUMPTION (TWh)	14087
CAPACITY NEEDED (MW)	(4334)

2. Model of system components

2.1. Model of a Solar Panel

2.1.1. Equivalent model of a solar cell.

Solar cells are one form of renewable energy systems which can be used to extract dc power from solar light. It is based on photovoltaic phenomena which use semi-conductor devices named photovoltaic cells [3]. An ideal equivalent circuit of a solar cell can be represented by an ideal current source in parallel with an ideal diode. In order to obtain a more accurate circuit, the effect of resistor R_p and R_s must be taken into consideration. Also, by looking to the depletion region of a cell, one can see a non resistive current path in parallel with the basic solar cell; this can be represented by two diodes D_1 and D_2. Fig. 1 shows a more accurate model of a solar cell.

This circuit known as the double exponential model of a solar cell where the output current becomes:

$$I = I_{sc} - I_{o1}\left(e^{\frac{q \times (V + I \times R_S)}{K \times T}} - 1\right) - I_{o2}\left(e^{\frac{q \times (V + I \times R_S)}{2 \times K \times T}} - 1\right) - \frac{V + I \times R_S}{R_P} \qquad (1)$$

Diodes D_1 and D_2 can be combined and a new diode ideality factor n is created, and if we assume the parallel resistance Rp = ∞, n takes a value between 1 and 2 and for ideal diodes n = 1. The new current equation is:

$$I = I_{sc} - I_o\left(e^{\frac{q \times (V + I \times R_S)}{(n \times K \times T)}} - 1\right) \qquad (2)$$

The derived solar cell model is based on what is called "The Five Parameters Circuit Model", and those parameters are reference temperature T_{ref} in K, reference irradiance G_0 in W/m^2, series resistance R_s in Ω, open circuit voltage V_{oc} in Volts and short circuit current I_{sc} in A computed at T_{ref} and G_0. All these values can be provided by the manufacturer datasheet [3].
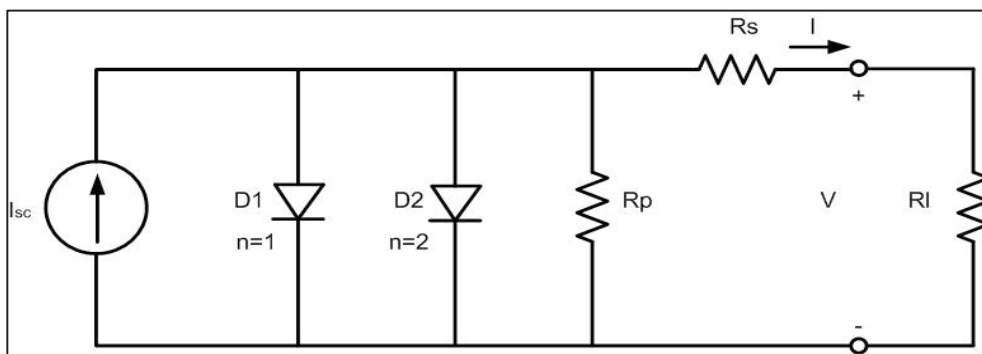

Figure 1 Real equivalent circuit of a solar cell [3]

2.1.2. MATLAB/SIMULING derived model

Based on the equation of the previous section, and using the five parameter model, the PV array model is built using SIMULINK software. The derived model shown in Fig. 2.-(a) is considered as a physical model and can be added to the 'SimPowerSystem' library.

The temperature and irradiance are set as input to the block while the voltage is the output measured at the controlled current source then fed back to the current equation in order to obtain the output current. The user can change the parameters of the block by double clicking on the block, the window of Fig-3 appears.

Notice that a single cell can deliver a small amount of power, for this reason a number of solar cells are connected in series or parallel to obtain the desired output power. In the derived model in figure 2, three arrays are connected in series and four in parallel (which makes a total of 12 PV arrays) in order to obtain 1.8 kW as output power. A configuration where several cells are connected together is known as photovoltaic array or simply PV array [4].

2.1.3. PV Characteristics

In this section we will examine the effect of irradiance and temperature on the PV array. Fig. 4-(a) examines the temperature effects on the PV array characteristics by considering $G = G_0$.
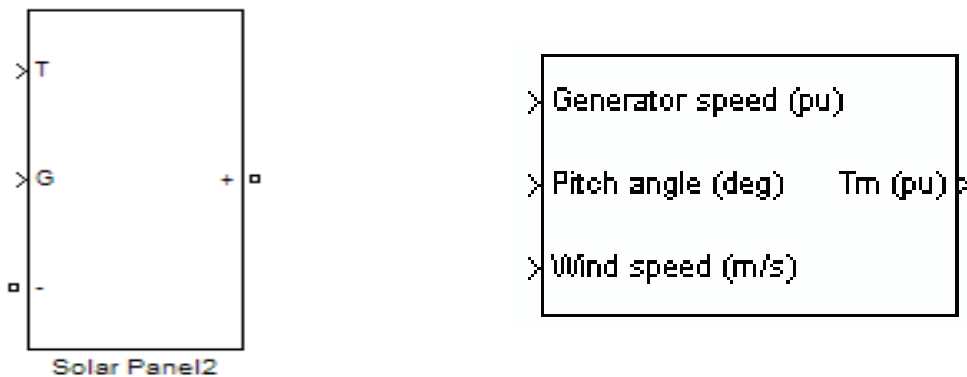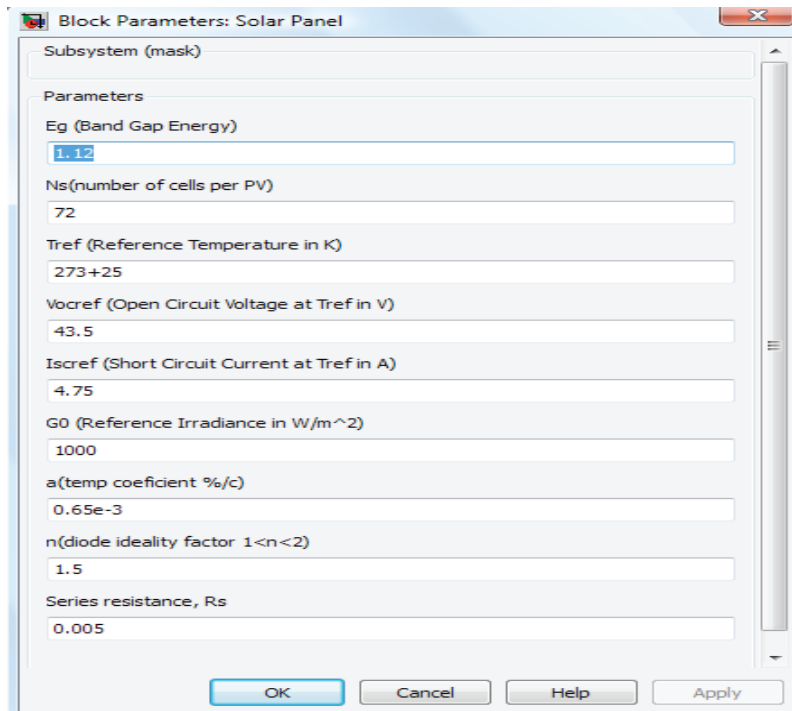
Figure 2. (a) SIMULINK PV array; (b) wind turbine model

Figure 3. PV model input parameters

As we can see on the power curve, as the temperature decreases the maximum extracted power increases. Also, we can notice that as the temperature decreases, the output current is almost constant and the terminal voltage increases. Fig. 4-(b) illustrates the effect of different irradiances with T= T_{ref}= 25°C.

By looking at the P-V characteristics, one can notice that as the sun irradiance increases, the maximum extracted power increases. However, as the sun irradiance decreases, the generated output current is lowered while the output voltage changes slightly for different irradiances.

2.2. Model of the Wind Turbine Generator Systems

2.2.1. Model of the turbine.
Based on the aerodynamic equations, MATLAB/SIMULINK software implements a variable pitch wind turbine model. The output power equation of the wind turbine given by Siegfried Heier is:

$$P_m = c_p(\lambda, \beta) \frac{\rho A}{2} v_{wind}^3 \qquad (3)$$

Where,

P_m	Mechanical output power of the turbine (W)
c_p	Performance coefficient of the turbine
ρ	Air density (Kg/m3)
A	Turbine swept area (m2)
v_{wind}	Wind speed (m/s)
λ	Tip speed ratio of the rotor blade tip speed to wind speed
β	Blade pitch angle (deg)

Fig. 2-(b) shows the wind turbine model as it exists in the SIMULINK library. This model is a p.u. model where the inputs to the turbine are the wind speed in (m/s); the blades pitch angle β in (deg) and the generator speed in p.u of the nominal speed. The output is the torque in p.u. [5].

The user can enter the parameters of the turbine in a dialog box that appears by double clicking on the model. The nominal mechanical output power (W) is chosen to be equal or higher than the generator's power rating. The base power of the electrical generator (VA) is equal to the generator power rating which is 5 kW. The base wind speed is 2 m/s and the maximum power at base wind speed (p.u. of nominal mechanical power) is 0.3 p.u. (K_p=0.3). Finally, the base rotational speed or the rotational speed at maximum power of the base wind speed is 0.3 p.u. of the base generator speed.

2.2.2. Generator model.
A permanent magnet synchronous generator (PMSG) is considered in this model as it is the best type of generators used in small scale wind turbines. MATLAB/SIMULINK implements a dynamical model (Fig. 5) for the permanent magnet synchronous machine. The machine can be operated in two modes: motor or generator by simply applying a negative torque for generator operation and positive torque for motor operation. Also the machine implements sinusoidal and trapezoidal models. For the sinusoidal model, it is assumed that the flux established by the permanent magnet is sinusoidal. For the trapezoidal machine model, it is assumed that the winding distribution and flux established by the magnets produce three trapezoidal back EMF waveforms [5].

2.2.3. Combined model.
Fig. 6 shows the turbine-generator model. The turbine is used to drive a 5 kW permanent magnet synchronous generator, and a PI controller is used to control the blade's pitch angle, where at high wind speed, the rotational speed of the PMSG exceeds its rating and β increases automatically to maintain a rotational speed below the rated value.
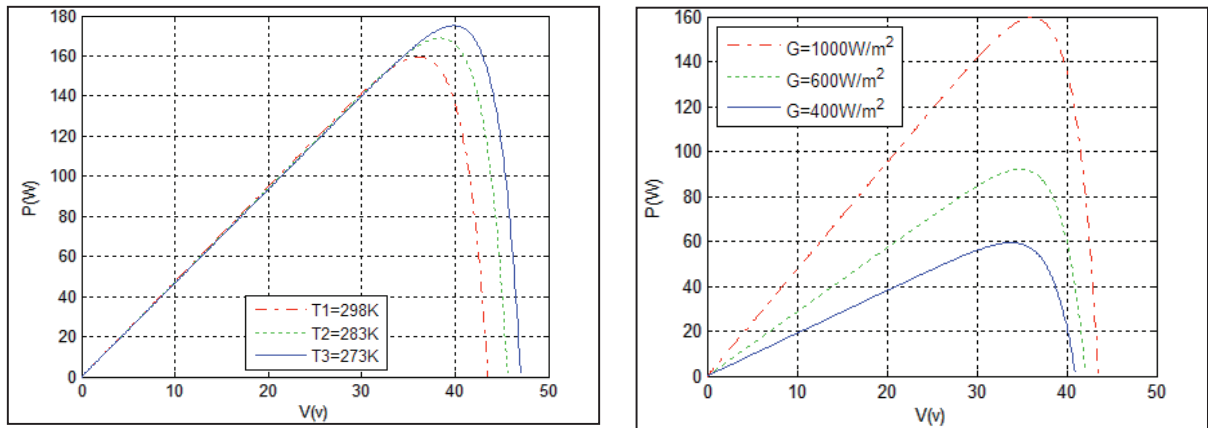
Figure 4. (a) Temperature effect on the output power of PV array; (b) Sun irradiance effect on the output power of PV array
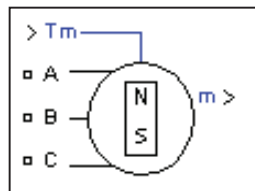

Figure 5. SIMULINK model of PMSG

2.3. Controlled Boost Converter

A boost converter is used to maintain a constant DC-link voltage of 350V. The ratio of the output voltage to the input is determined by setting a certain duty cycle to the PWM generator. To maintain a constant output voltage while the input is varying, one should control the duty cycle of the PWM generator. The circuit topology is shown in Fig. 7. The output voltage of the boost converter is measured and subtracted from a reference voltage to generate an error signal. The error signal is fed to a PI type controller which specifies the duty cycle that minimizes the error signal. Notice that a limiter is used to prevent the value of the duty cycle from being higher than 0.9 or the boost converter will become unstable.

2.4. Grid Tie Inverter

A grid tie inverter also known as synchronous inverter is used to convert the DC power generated by the renewable energy system to AC power that matches the grid conditions. Power flow control is performed on the inverter in order to transfer maximum power from the renewable system to the grid side. MATLAB/SIMULINK implements a universal power converter with different topologies and power electronic devices in the Sim-Power-Systems library. The block implements single and 3-phase inverters using naturally commutated power electronic devices such as Thyristors or Diodes, and forced-commutated devices like GTO, MOSFET and IGBT. The user can choose different topologies in the dialog and parameter box [5]. Fig. 8 shows a 3-phase IGBT bridge inverter used in the design.

3. Distributed energy system design

Fig. 9 shows the circuit topology of the proposed design. The system is On-Grid without storage, in case of extra generation; the power excess is injected in the grid. The system consists of a 1.8 kW photovoltaic solar plant and a 5 kW wind turbine. The output of the wind turbine is unstable because of the varying wind speed (output voltage has different magnitudes and frequencies). A 3-phase diode bridge rectifier is used to convert the turbine power from AC to DC. The power generated from PV system is DC so there is no need for any AC-DC conversion. A controlled Boost inverter is used to maintain constant DC-Link voltage of 350 V and the control of each unit is individual. Diodes D_1 and D_2 play an important role in the system as they allow unidirectional current flow. In such topology, all generating units can be replaced by one source having a total current of $I_{D1} + I_{D2}$. Notice that different power sources can be added

to this circuit and more output power can be generated [6]. The overall system is built and simulated using MATLAB/SIMULINK and is shown as blocks in Fig. 10.

3.1. Power Flow Control

The objective of the proposed design is to transfer the maximum power that can be generated by the wind turbine and the PV system under certain sun irradiance and wind speed conditions to the grid/load side. To explain how this can be done, consider the circuit in Fig. 11.

A local load is connected to the grid side, and the inverter-grid voltages are separated by a transfer reactance X_M. Then the active power flow can be described by the following equation:

$$P = \frac{V_G \times V_C}{X_M} \sin\partial \tag{4}$$

Where V_G is the per-unit grid voltage and V_C is the per-unit inverter voltage. X_M is the per-unit transfer reactance between the grid and the inverter; it is the equivalent reactance of the transformer, and the link inductor. From equation (4), the power flow can be controlled using ∂ which is the difference between the inverter's phase angle and the grid phase angle. The phase angle of the inverter is used to control the power flow. Also the inverter is used for reactive power compensation and should deliver the load reactive power demand [7-9].
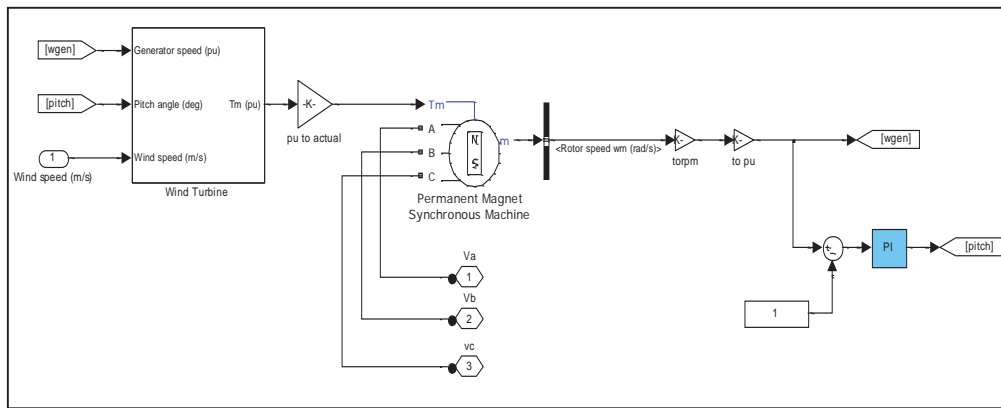

Figure 6. Turbine-Generator model

Now an important question arises: Given a temperature and irradiance conditions, and a wind speed, then what is the angle ∂ so that maximum power is transferred to the grid side? To answer this question, one can easily show that:

$$\partial = \sin^{-1}\left(\frac{P_{max} \times X_M}{V_G \times V_C}\right) \tag{5}$$

Equation (5) is used to implement the control system. Given P_{max}, ∂ is computed and the power flow to the grid is controlled.
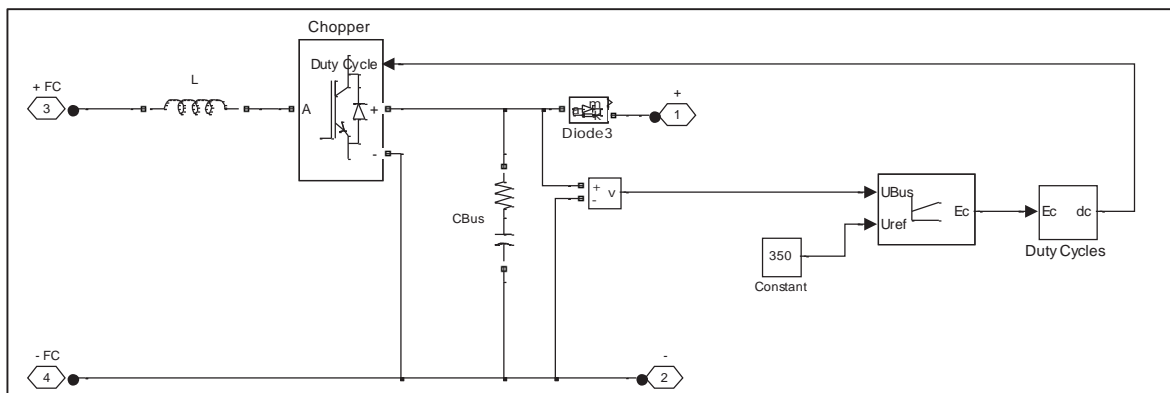

Figure 7. SIMULINK equivalent circuit of a Controlled Boost Converter [5]

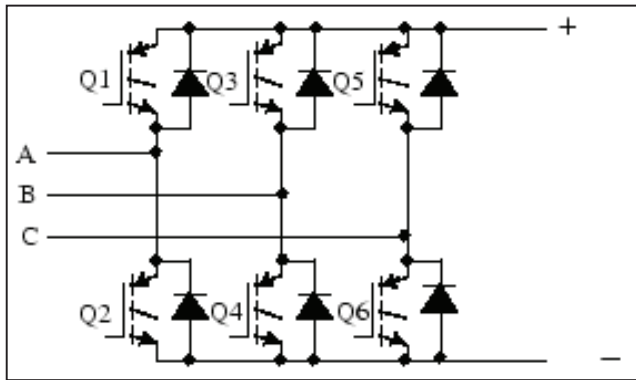Figure 8. Equivalent circuit of a three Φ IGBT bridge inverter

3.2. Maximum Power Point Tracking (MPP)

In order to compute ∂, we should compute the maximum power that can be extracted from the solar plant or wind turbine given sun irradiance and wind speed. Maximum power point trackers MPP are used for this purpose.

3.2.1. Photovoltaic MPP.

Each solar array has a current-voltage characteristic with a unique point known as the maximum power point MPP. Several techniques for MPP tracking can be applied such as Neural Network Control, pilot cells and digital signal processor based implementation, but the "Perturb and Observe" are the best techniques used for low cost implementation. "Perturb and Observe" is a technique that searches iteratively and continuously for the maximum power point [6], [10]. The value of the increment C should be small (0.2 for example) in order to get a smooth response for the algorithm. Any changes in the sun irradiance or temperature will be detected by the algorithm and the new maximum power point is detected.

3.2.2. Wind turbine MPP.

The wind turbine MPP is very easy to implement as it is based on the per unit output power equation of the turbine:

$$P_{m_{pu}} = k_p c_{p_{pu}} v^3_{wind_{pu}} \tag{6}$$

Given the wind speed, one can easily compute $P_{m_{pu}}$ since the power gain K_p is constant and is 0.3 and the power coefficient C_p is also constant for β=0° and is equal to 0.48 p.u. For high wind speeds the pitch angle β increases automatically as described before and C_p changes, but we should notice that P_m could not exceed the rated value of the permanent magnet generator [5]. For this reason, and for all wind speed value at which P_m is greater than the generator ratings, the MPP saturates at an output equal to 5 kW.

4. Simulation and results

The simulation results are presented in this section. To demonstrate the effectiveness of the proposed system design a 4 kW (Active Power), 700 VAR (Reactive Power) load is supplied by the grid and the hybrid system. Different scenarios are shown in Fig. 12 related to the variation in wind speed, sun irradiance temperature and EOL (Electricity of Lebanon) supply, where each one of this parameter will be divided into several zones indicating different value brackets.
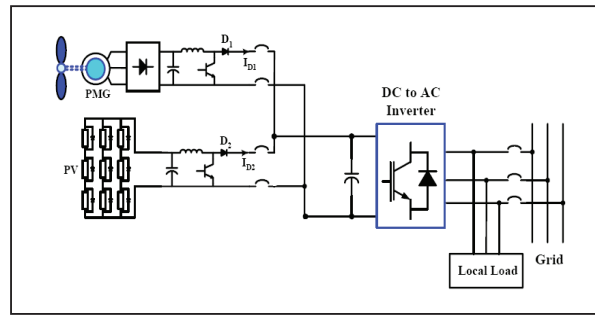
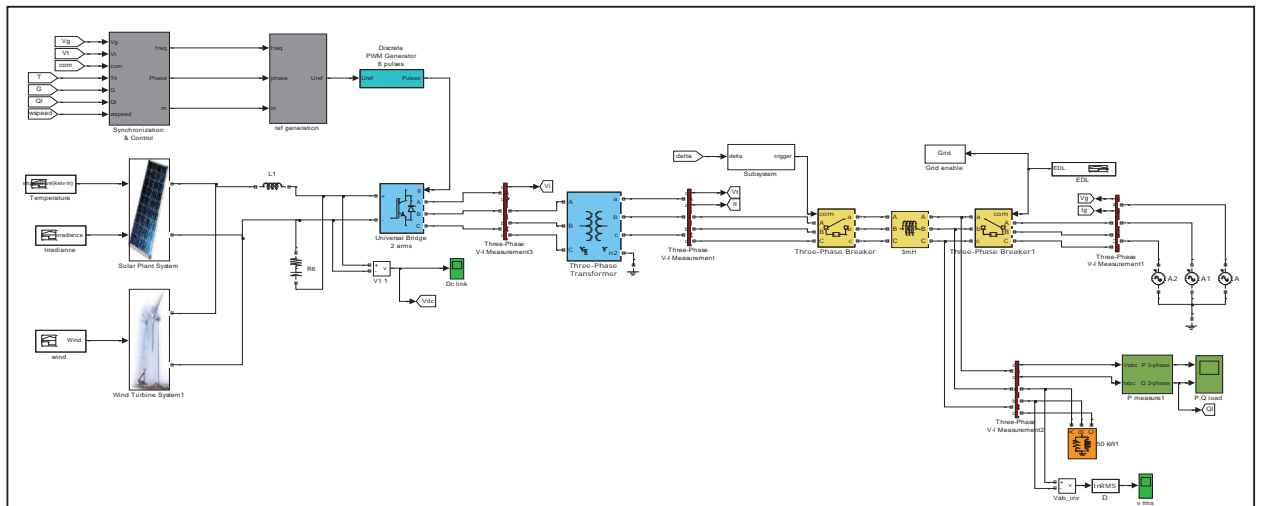Figure 9. Schematic of the grid connection of a hybrid energy system [6]

Figure 10. Overall SIMULINK system design

The DC link voltage was adjusted to a reference value of 350 V while a pitch angle control was used in order to maintain the rotational speed of the PM generator below the rated speed of 1 per unit. Fig. 13 shows the inverter, grid and load real power flow. Renewable energy sources were considered to be our primary source of power while grid is used as a secondary source. Notice that the maximum power that can be delivered by the system is 6.8 kW.
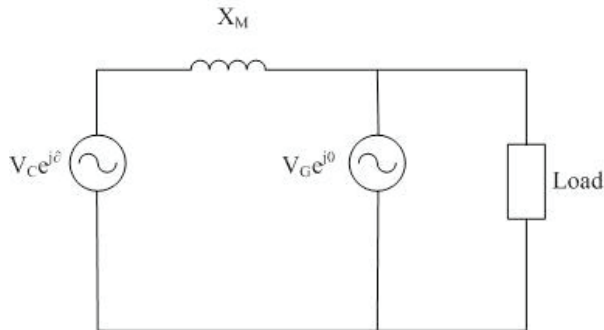

Figure 11. Power flow control [7]

In Zone 1 of the real power in Fig. 13, the contactor was open and in Zone 9 where no sufficient wind and solar energy, no power can be delivered from the inverter, and all the 4 kW real power will be taken from the EOL grid. For Zone 2, about 6.8 kW can be delivered by the inverter where 4kW are transferred to the load and the excess of 2.8 kW can be delivered to the grid. Zone 4 illustrates the case where no power can be drawn from the wind turbine system and only 600 W can be delivered by the inverter and the remaining 3.4 kW will be taken from the grid. Zone 5 illustrates the case where the EOL grid goes off and all the 4 kW power is delivered from the renewable energy system. We should mention here that if the inverter can deliver more than 4 kW, the excess of power could not be sold to the EOL grid. Zones 6 and 7 illustrate the case where no power can be drawn from the solar panel system. However, for different wind speeds, different power can be drawn from the inverter. In Zone 6, about 5 kW can be drawn where 4 kW is taken by the load and the remaining 1 kW would be delivered to the grid. However, in Zone 7, only 3 kW can be drawn from the inverter and the remaining 1 kW will be taken from the grid. Finally in zone 10, the delivered power from the inverter is about 2.7 kW and the remaining power of 1.3 kW is taken from the EOL grid.
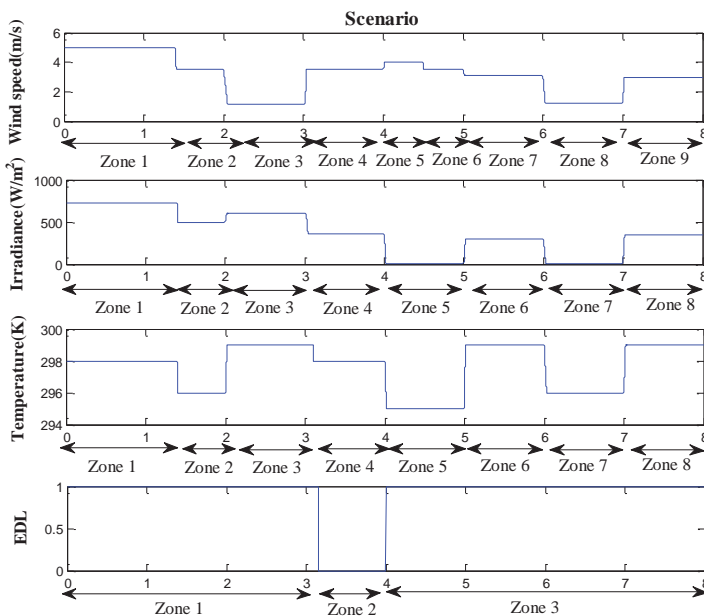

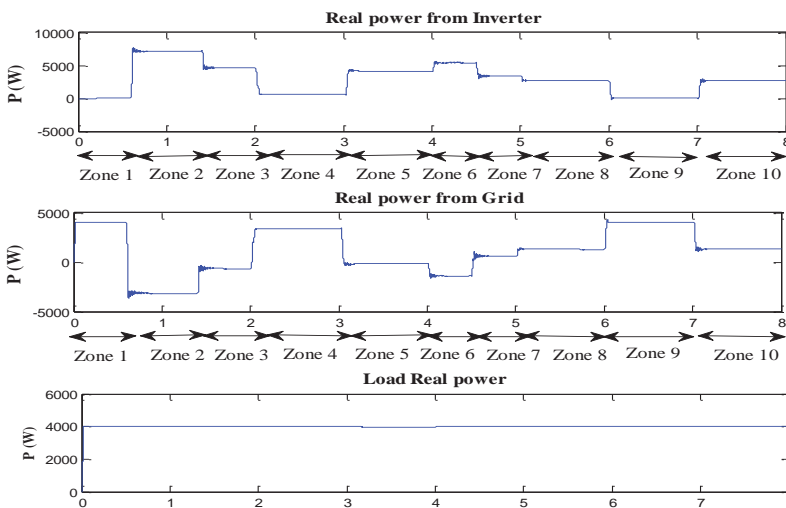Figure 12 Different scenarios for wind, irradiance, temperature, and EOL grid

Figure 13 Inverter, grid and load real power transfer

5. Conclusion

In this paper, a new circuit topology was proposed for hybrid energy systems including wind and photovoltaic which will be used in distributed energy application. Simulation results proved the feasibility and reliability of the proposed system where power can be delivered from both the inverter and the grid. However, in case of extra power from the inverter, this power can be sold to the grid.

As there are no official data for wind and solar in Lebanon, measurements were taken in several regions and indicate that this country is rich in renewable energy sources. Small private hybrid-renewable energy systems were implemented in Lebanon, but no power was sold. However, several steps must be taken by the government in order to encourage the use of renewable energy system such as:

- Updating law 462 where EOL can buy the excess of power delivered by the renewable energy sources and assumes responsibility for its distribution.
- Reducing income taxes for any individual implementing a renewable system.
- Providing special offers and loans for those who want to install a renewable power plant, as the case of SWH (Solar Water Heater) systems.

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