Performance Analysis of a Hybrid Microgrid with Energy Management

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Abstract-In a hybrid microgrid system, various renewable energy resources may be integrated and modeled on-site, in such a way as to provide an optimal, consistent, and sustainable energy production at a cost-effective rate throughout the year. In this paper, a microgrid prototype consisting of a wind turbine and a photovoltaic (PV) panel is modeled and thoroughly investigated through various changes in inputs. The long-term goal of this work in IUM is to develop a concise and complete microgrid system model that can be used to simulate and fully understand its behavior and operation. The proposed model including power sources, power electronic converters, and load has been modeled in MATLAB/Simulink.

Keywords-PV microgrid; grid modeling; microgrid; wind turbine; battery

I. INTRODUCTION

During the recent years, there was a huge demand of energy from vital sectors such as the manufacturing industry, the transportation system, and general construction industry which indicated a steady growth in economic development. However, this energy is related to environment concerns because the use of fossil fuel and coal for the generation of electricity generation emits greenhouse gases (GHG). Thus, numerous stake holders aim the developing countries to use clean and green energy with financial support [1-2]. With the steady increase in global population, the demand for energy has increased dramatically and this has led to a high pressure on actual energy infrastructures to generate power above their nominal capacity. The development of electric power generation methods to make the Kingdom of Saudi Arabia a logistical center connecting three continents and thus enhance sustainable economic growth and competitiveness, while achieving convergence between all services to meet the Kingdom's needs by raising the level of protection, rationalizing energy, and improving the quality of operations and performance for providing effective services to all beneficiaries, is in line with Saudi Vision 2030 [3-5]. Power generation projects are among the most important projects that the governments seek to present to their citizens to develop cities, provide basic services to the society and raise the state's economy by owning an integrated power generation system [6-8].

To extend the national grid for rural areas and remote places, a high price has to be spent for building such large power networks. This has prompted decision makers to look for alternatives energy resources such as renewable energy in local levels [9-12]. To address the challenge of this global developmental crisis, numerous meetings have been conducted between government and private stakeholders without much success bearing in mind that the population will be without any access to electricity [13-14].

The use of the alternative renewable sources such as hybrid microgrid systems is a way of achieving this objective. This will allow the generation of eco-friendly electricity in remote areas by suppressing the effect of climate change. Recently, and as a short term solution to this energy crisis, hybrid microgrids have been thoroughly used as an alternative for the generation and distribution of renewable energy in remote locations [15-18].

A Microgrid system is usually composed of distributed energy resources like photovoltaic panels, wind turbines, fuel cells, or micro turbines that may be connected to the distribution network at a medium voltage. Microgrids can also work off the main grid to meet customer needs, improve reliability, lower emissions, and improve power quality at a reduces price. The optimal use of hybrid microgrids assets as an alternative to the main grid extension has allowed for electricity generation at a reduced overall price [19-20].

In this paper, energy management with specific aspects related to remote localities is proposed, powered solely by

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renewable resources where the grid extension is not plausible. These solutions can be applied for isolated water pumping, irrigation, household applications, etc. In the future, with the development of more efficient technologies, the proposed solutions will be of great interest for telecommunications applications and hydrogen storage. Recently many research works have been published on the field of modeling and simulation of isolated hybrid systems [21-24]. In this paper, we mainly focus on the study of strategies for the energy management in a hybrid microgrid. Three different energy management strategies are considered: Photovoltaic system, wind turbine, and batteries. The major contribution of this paper is the presentation of a simulation model of a hybrid microgrid energy system made up of PV panels, wind turbine, and battery for storage. This paper provides the overall description of the proposed methodology of the management strategy of the system. The effectiveness of the proposed hybrid microgrid energy system is confirmed through the simulation under several situations such as variation in power demand.

II. HYBRID AC/DC MICROGRID

Microgrids are effective systems for managing dispersed resources like small-scale distributed generators and renewable energy resources. The microgrid structure allows for more efficient operation which could lead to lower emissions and fewer power outages. Microgrids can be made up of a complicated mix of AC and DC sources, as well as AC and DC loads, and power electronic interfaces. The benefits of both AC and DC microgrids are combined in a single network architecture with hybrid AC/DC microgrids. By permitting seamless connection to numerous AC and DC sources and loads, it decreases the losses associated with multiple conversions from DC to AC and vice versa. It may also be linked to the national grid or used as a stand-alone power source. When connected to the utility grid, the AC and DC microgrids receive energy from it to balance between load demand and supply, resulting in a acceptable power balance with the grid. When there is an excess of power in the AC and DC microgrids, the power will flow to the utility grid. On the contrary, when there is a shortage of power in the AC and DC microgrids, power is returned back to the AC and DC microgrids by the utility grid. Usually, the Energy Storage Systems (ESSs) are used primarily to compensate any shortage of energy since the generating units are supposed to provide the majority of the energy consumed in the system. Thus, the AC and DC microgrids will deliver energy with a steady bus voltage and reduced harmonics to the utility grid. The main converter in the microgrid will minimize any unbalance occurring from the loads and when the output of the DC sources exceeds the output of the DC loads, the converter acts as an inverter, transferring power from DC to AC.

III. MODELING OF THE MICRORGID

A. PV Array with MPPT

Usually, the sun is considered as a potential source of energy as it is consistent and clean, as opposed to other types of energy that contaminate the atmosphere and the environment, such as coal, oil, and oil derivatives. A PV cell is usually considered as a current source in parallel with a diode as shown in Figure 1. With the increase of intensity of sun light, current is produced by the PV cell [18].

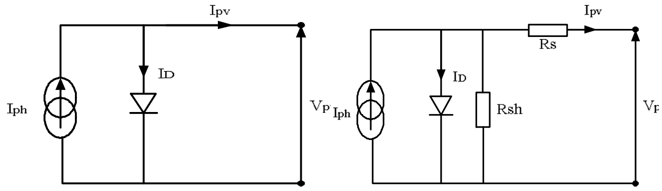

Fig. 1. Electrical model of a solar cell.

Ideal case:

$$I_{pv} = I_{cc}\frac{E}{E_r} + k_{isc}\left(T - T_r\right)\frac{E}{E_r} - I_s\left[\exp\left(\frac{V_{pv}}{V_T}\right) - 1\right] \quad (1)$$

Real case:

$$\begin{gathered} I_{pv} = I_{cc}\frac{E}{E_r} + k_{isc}\left(T - T_r\right)\frac{E}{E_r} - \\ I_s\left[\exp\left(\frac{V_{pv} + R_s I_{pv}}{V_T}\right) - 1\right] - \left(\frac{V_{pv} + R_s I_{pv}}{R_{sh}}\right) \end{gathered} \quad (2)$$

We use the model of (1) and (2) [18], due to the difficulty of estimating the PV system's behavior. We may be able to determine the panel's I-U and P-U properties using this approach. It may also allow us to adjust the voltage, current, and power while changing the number of cells in series and parallel in the panels. The modeling of a panel composed of N_s modules in series and N_p modules in parallel is given. The diode current I_p is obtained by [18]:

$$\begin{gathered} I_p = N_p\left[I_{ph} - I_0\left(\exp\left(\frac{\frac{V_p}{N_s} + \frac{R_s\, I_p}{N_p}}{V_T}\right) - 1\right)\right] \\ - \frac{N_p\, V_p}{N_s\, R_{sh}} - \frac{R_s\, I_p}{R_{sh}} \end{gathered} \quad (3)$$

Figure 2 shows the I-V characteristics of the panel as defined for this application at various ambient temperatures and a constant irradiation of 1000W/m^2. It can be seen that when the temperature rises, the power produced by the PV panel decreases. Temperature fluctuations have little effect on the short circuit current. Figure 3 depicts the PV panel's I-V characteristics at constant temperature of 25°C and various irradiation values. The higher the degree of solar irradiation, the more power the PV generates. As a result, any change in the irradiance level will alter the short circuit current value proportionately.

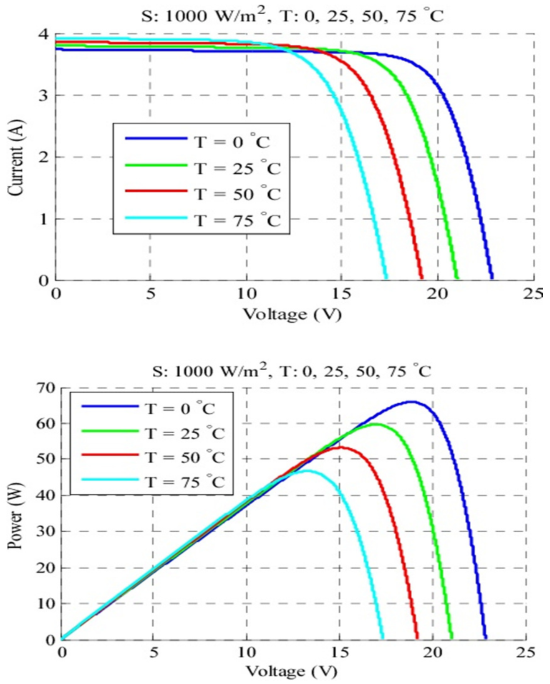

Fig. 2. I-V characteristics at different temperature and constant irradiance of 1000W/m^2.

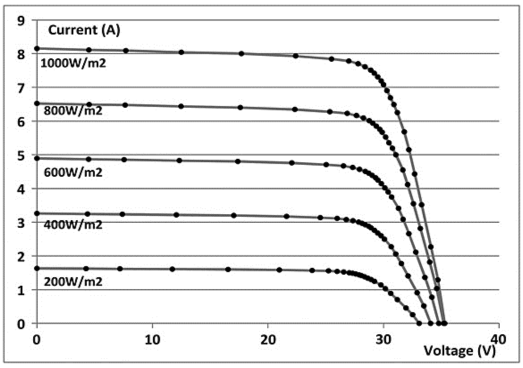

Fig. 3. I-V Characteristics of PV at constant temperature of 25^{0}C and different irradiances.

B. Wind Turbine Modeling

Wind energy conversion is the world's fastest-growing source of new electric generation, and it is likely to stay that way for a long time in future. It is more appealing than other sources because of its extended lifespan, emission-free operation, and low cost. These turbines supplement the use of other electric power sources by delivering the most cost-effective solution in a variety of situations. Figure 4 shows the steady state features of the wind turbine as modeled by its variable pitch. In the first input, the per unit of the generator base speed is taken and the synchronous speed is modeled as the base speed of a synchronous or asynchronous generator. The second and third inputs are the blade pitch angle and the wind speed in m/s. The base speed of the permanent-magnet generator may be considered as the speed for nominal voltage generation and no load application. The rest parameters, such as the drive train's stiffness, will be taken as infinite whereas the turbine's friction factor and inertia will be combined with those of the generator. The following equation calculates the turbine's output power [16]:

$$P_m = C_p(\lambda,\beta)\frac{\rho A}{2}V_{wind}^3 \quad (4)$$

We can use numerical integration using the trapezoidal rule to determine the total amount of electrical energy produced by the panel [16]:

$$E = \int_{sunrise}^{sunset} P(t)dt \sim \sum_{i=1}^{N-1}\frac{1}{2}(P_i + P_{i+1})\Delta t \quad (5)$$

For a constant step size we can calculate the energy production as [16]:

$$E = \int_{sunrise}^{sunset} P(t)dt \sim \left(\frac{1}{2}P_1 + \frac{1}{2}P_N + \sum_{i=2}^{N-1}P_i\right)\Delta t \quad (6)$$

Figure 4 depicts the Simulink mathematical model of a wind turbine. The generator speed of the nominal generator speed, the pitch angle in degrees, and the wind speed in m/s are used as the three inputs. The output is the torque applied to the generator shaft which can be obtained by dividing the rotational speed by the wind speed to get the tip speed ratio in pu value.

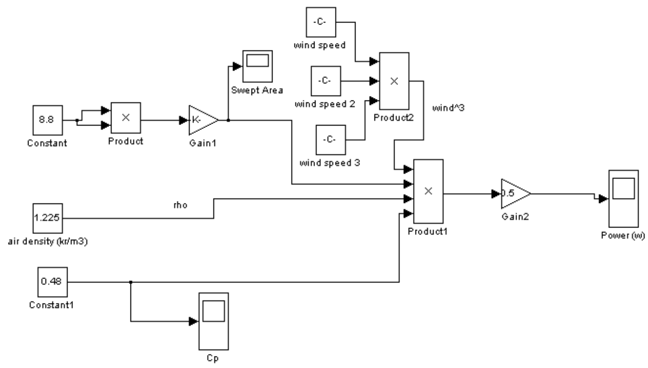

Fig. 4. Simulink mathematical model of the wind turbine.

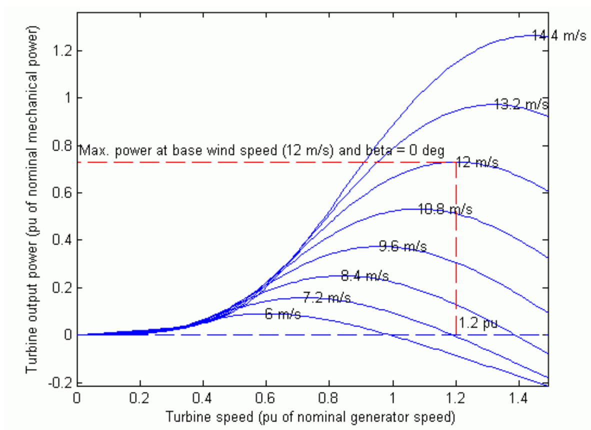

Fig. 5. Turbine power characteristics with wind as parameter.

Figure 5 shows a series of mechanical power curves versus wind speed changes. It can be seen that average wind speed of 3.81m/s is obtained as the base wind speed. Moreover, we have obtained the maximum power as 0.73 pu (kp = 0.73) at base wind speed, and the maximum rotational speed is 1.2 pu at base rotational speed.

C. Battery Operating to Support the PV System

Storage energy is used in this simulation to help the PV system fulfill the load power requirements. Because the battery active power reference (P_A) will be led by (7), it might be considered the foundation of a stand-alone system. The battery will not only be used to supply its energy to help the PV system (P_{PV}) meet the needs of the load's demand (P). It will also store the energy generated by the PV system when it exceeds the power demand of the load [17].

$$P_A = P_{PV} - P_L \quad (7)$$

Figure 6 illustrates the Simulink model of the battery and in Figure 7 we can notice the presence of three regions related to the flow characteristics of the battery. In the first region and during the charging of the battery, an exponential drop in voltage occurs. The area corresponding to the available charge in the battery before the drop of the voltage below its nominal voltage is depicted in the second region. The third region corresponds to the discharge cycle of the battery as the voltage drops. This drop depends on the type of the battery. Moreover, the battery will recharge if the current becomes negative.

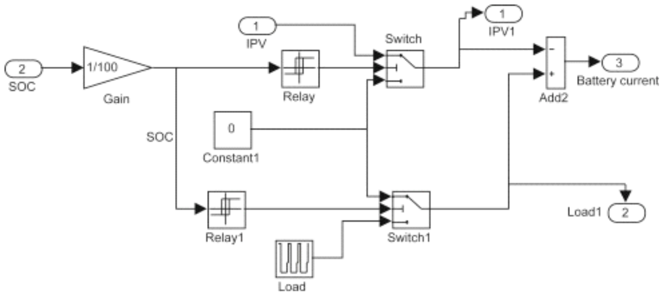

Fig. 6. Battery model.

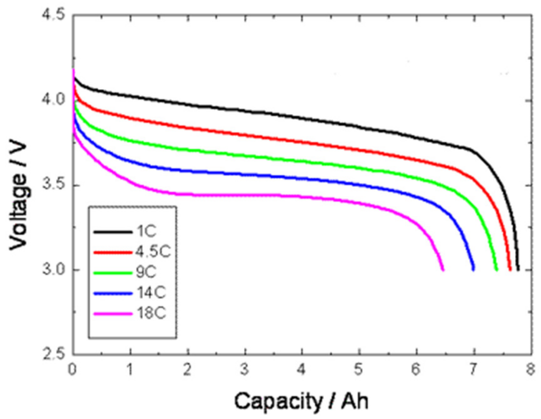

Fig. 7. Charge and discharge characteristics of the battery.

As can be seen in Figure 7, the value is not always zero because of the existence of power losses (inductors and equivalent resistances) which are not supported by the battery.

IV. THE PROPOSED POWER MANAGEMENT SYSTEM (PMS)

In this paper three different management strategies are compared. The main objective of this current study presented in this paper is to propose three different energy management strategies that can satisfy the following criteria:

- guarantee the electrical energy required by the user,
- manage efficiently the resources, and
- minimize the excess energy.

The management strategy will define the autonomous control of the power sharing scheme with the local load demand. It will also guarantee the reliability operation of the generating units' production.

The PMS aims to ensure power balancing among generating units as well as load management during power outages, with vital and critical loads being prioritized. This is important to prevent the DC bus voltage from collapsing due to the microgrid being overloaded and to keep the circulating currents to a minimum. The sub-units are related to the DC bus at which the output is reversed. Moreover, the PMS is designed to provide power that has a larger renewable fraction, and can adjust all of the electric parameters supplied by the inverters based on the energy demand. However, the PMS will not rely on communication protocols of the producing units to increase the network's overall efficiency. The PMS algorithm, which is used to determine the best network configuration for the PV-Wind-Battery category, employs a cycle charging and load following dispatch strategy. The network's operational cycle is described below.

A. Energy Management A ($P_{PV} + P_W < P_{load}$)

Due to the changing nature of the renewable sources caused by seasonal climate variations, the energy produced by these sources is either insufficient or unavailable in this stage. The energy stored in the battery will be used to supply power to the local community, provided that the battery storage is within the operation's minimal SOC. The system will remain in this condition until the restoration of power or until the battery' capacity falls under 25%.

B. Energy Management B ($P_{PV}+ P_W > P_{load}$)

The required load demand energy to the local community will rely mainly on the renewable sources and any excess of power will automatically be stored in the battery bank. The battery is in a charging state at this point.

C. Energy Management C ($P_{Load} < SOC_{min}$)

When the battery's SOC falls below the minimum permitted limit of 25% and renewable energy is unavailable, the system's operation is taken over by the diesel generator. The generator is offered as a backup to avoid the system from completely collapsing if the renewable energy sources are unavailable for an extended period of time. No discharge from the battery will occur in this case since any extra power will be stored in the battery bank.

D. Discussion

When the combined power of the PV panel and the wind turbine exceeds the load requirements, the excess electricity will be stored in the battery. If, on the contrary, this power is insufficient to satisfy the load requirement, the battery will begin to discharge its stored energy to service the load. If the battery runs out of the stored energy, and electricity from the PV and wind turbine system is not available, the generator kicks in, providing the needed power to service the load with an excess as charge in the battery system.

V. Conclusion

A thorough evaluation of the mostly often utilized techniques in the literature for AC and DC microgrids was conducted in this paper in order to discover strategies that can be applied in hybrid microgrids. The main functions that a management plan should provide have been gathered, and a classification of the mostly studied hierarchical controls has been developed. The effectiveness of a hybrid microgrid for utilizing distributed renewable energy while meeting local load demand has also been discussed. Microgrid modeling and operation modes were also analyzed and presented. The microgrid serves as a vital link between dispersed generation and renewable energy. The approaches for power management are depicted. When opposed to a standard grid, the nature of the microgrid is irregular and intermittent.

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