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Sustainable Development of Electrical Systems and Renewable Energy Resources Management for Coastal City using AI Technology

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ABSTRACT

This article explores a new approach to building electrical infrastructure for coastal cities, making them clean energy producers rather than consumers. Using Ain Sokhna, Egypt, as a model, the proposed system combines solar panels, wind turbines, battery storage, and a connection to the main electricity grid to create a flexible, eco-friendly energy setup. The goal is to help coastal cities utilize their natural resources, sun, and wind to generate electricity, especially during high-demand seasons driven by tourism. The system is designed to adapt to seasonal changes in energy use. During sunny or windy days, it generates power, storing any extra in batteries or sending it back to the grid. On days when less energy is produced, it can pull from stored power or draw from the grid. This creates a balanced, efficient flow of electricity that supports the city's needs without relying entirely on traditional power sources. Early simulations show the system is both technically and financially viable. It could reduce energy costs and offer long-term savings with minimal maintenance. Looking ahead, artificial intelligence technology will be added to help the system make smarter real-time decisions based on weather, energy use, and grid demand. A user-friendly dashboard is also planned, allowing remote monitoring through a web or mobile app. Overall, this model shows that coastal cities like Ain Sokhna can not only meet their own electricity needs but also contribute energy back to the grid, transforming them into valuable energy assets.

1. Introduction

The clean Grid contain main components as Electrical power grid system in emergency with essential renewable resources wind power, PV, storage and demand-side response to feed the largest amount of clean energy consumption as the primary goal with minimum cost as possible for achieving power balance, grid reliability, constrain limits of the energy storage system, demand-side response, and wind power and PV output limits. the study of Simulink simulates comparative analysis, the energy storage and the demand-side response can effectively improve the wind power and PV consumption rate to get the stability and economy [1]. In wind farms, there are different configurations for small group of the wind turbines to reduce wake effect losses and enhance the performance of wind turbines which relates to PV energy generation grid. An additional energy can be

produced at wind farm site by implementing solar PV power plants in unutilized land with wind farm. Due to non-linear behaviour of wind speed, wind energy conversion system is must be controlled when feeding a fixed load demand [2]. The electrical networks are difficult and contain different generation system which has different behaviour to generate energy. One of the ways that is used to overcome this problem is the use of electrical separated generation directly to the demand in closed zone which decrease the reliability of system against the sudden faults or generation disturbance, Therefore the micro-Grid and hybrid electrical system will be used to achieve the stability. These networks are called standalone microgrid systems. For example, a standalone micro-grid system consisting of a Photovoltaic (PV) and Wind Energy Conversion System (WECS) based Permanent Magnet Synchronous Generator (PMSG) is being designed and controlled. Fuzzy logic-based Maximum Power Point Tracking (MPPT) is being applied to a boost converter to control and extract the maximum power available for the PV system. The control system is designed to deliver the required energy to a specific load, in all scenarios. The excess energy generated by the PV panel is used to charge the batteries when the energy generated by the PV panel exceeds the energy required by the load. When the electricity generated by the PV panels is insufficient to meet the load's demands, the extra power is extracted from the charged batteries. In addition, the controller protects the battery banks in all conditions, including normal, overcharging, and over discharging conditions [3]. The most suitable design and design evaluation of a hybrid microgrid based on solar PV panel, wind turbines, batteries, and diesel generators were arranged in special grid. The conventional grid-tied mode was used in addition to dispatch strategy-based control. The Case study test locations were oriented to the loads in Pabna University of Science and Technology (PUST), Pabna, Bangladesh. Big data was chosen to determine the power system-based behaviours (electrical power, current, voltage, and frequency) of the proposed hybrid system, while a derivative-free algorithm was used for the expense, optimal size, and emission assessments under certain constrain. While developing the microgrid, load following (LoF) and cycle charging (CyC) control were employed [4].

Microgrids can significantly illustrates the electrical distribution system by implementing an effective energy management system. The proposed hybrid optimization approach aims to provide constant power regardless of the generation discrepancy and should prevent the early deterioration of the storage devices and replaced with the battery of Electric vehicle. This Case study represents a dynamic control system based on the Fuzzy-Sparrow Search Algorithm (SSA) to provide a reliable power balance for microgrid (MG) operation. The proposed DC microgrid integrating renewable energy sources (RES) and battery storage system (BSS) as sources are designed and evaluated, and the findings are further validated using MATLAB Simulink simulation. In comparing the hybrid SSA strategy with the most widely used Particle Swarm Optimization (PSO) based power management, it was observed that the hybrid SSA approach was superior in terms of convergence speed and stability. The effectiveness of the given energy management system is evaluated using two distinct modes, the variation of solar irradiation and the variation of battery state of charge, ensuring the microgrid's cost-effective operation [5].

The maximum power point tracking (MPPT) was utilized for two different systems, Photo Voltaic energy and wind energy which is changed due to weather conditions around year. The output of simulation prove that the potential at the point of common coupling was constant. Furthermore, the injected current of the grid side was synchronized with grid side voltage. In addition, the injected energy-to-utility grid was around energy delivered by the hybrid PV and wind system. Wind Turbine (WT) Model The wind turbine is modelled by an aerodynamic input torque that drives a DFIG. The captured mechanical power (Pmech) that is established by the turbine which is proportional with the cubic of wind velocity [6].

The wind is one of several renewable energy sources that have the potential to produce electrical energy. Wind conditions that are not the same between places affect the energy

produced. This wind condition is closely related to wind speed, the wind speed has an essential role of the output torque of wind turbine, so an experiment is needed to determine the effect of wind speed on the power generated on the PLTB prototype [7].

Lithium ion (Li-ion) batteries have been extensively used in consumer electronics because of their characteristics, such as high efficiency, long life, and high gravimetric and volumetric energy. In addition, Li-ion batteries are the best attractive technology candidate as electrochemical stored energy system for a lot of station applications, as well as power source for sustainable automotive and back-up power supply applications [8].

Energy is very important for the world to maintain all other essential components of civilization and to raise living standards. Issues facing traditional energy sources include rising fossil fuel costs, environmental concerns, to keep the human health. Researchers are optimistic that they will be able to provide the sustainable studies about the renewable energy sources. Examples of clean and infinite sustainable energy sources are the sun, wind, biomass, fuel cells, and water. Among the various renewable energy sources, solar energy is widely utilized to produce electricity because of its easy maintenance and low cost of operation [9].

2. Material and Methodology

Management of Renewable Resources Using AI to feeding the energy for coastal city with Sustainable study for three Miga watt consumption from hybrid electrical system two thousand and half kilo watt PV with one thousand kilo watt wind energy with Fuzy logic controller using AI technology, Making the hybrid renewable system a good alternative to standard grid tie Using AI technology without any Risk for Load using (P&O) Algorithm. Sustainable Study must be oriented with different operation modes to feed the coastal city without any Energy trip using the best resources of clean Energy which is found in PV solar system and Wind turbine Energy to support the environment. At Emergency Case, Electrical Grid is used to feed the Load when the renewable resources are out of duty.

In response to the growing energy demands and environmental challenges facing Egypt and the world, this research represents a Hybrid Renewable Energy Management System designed for sustainable, resilient, and cost-efficient power delivery. The system integrates Photovoltaic (PV) solar panels, Wind turbines, and a Battery Energy Storage System (BESS) with intelligent control logic to ensure continuous power availability while minimizing dependence on the national grid. This hybrid approach not only capitalizes on the region's abundant solar and wind resources but also introduces smart control algorithms that manage energy flows based on supply-demand balance, battery state-of-charge (SOC), and grid availability. The research is implemented using MATLAB Simulink R2024a, combining both standard and specialized power systems, with custom-coded logic in MATLAB Function blocks and optional fuzzy logic-based enhancements. The system simulates real-world energy scenarios across different seasons and operating modes, ensuring optimized resource usage and fault tolerance. It is a strong candidate for real-world deployment in remote or off-grid coastal regions where reliability, autonomy, and sustainability are crucial. in order to bring back balance to the environment and make the human footprint on earth less destructive to the environment.

Microgrid contain Battery, Power Grid, PV System, Wind power station which is controlled using Fuzzy Logic Controller to simulate the different operation modes of Coastal City 3 MW as in Figure (1)

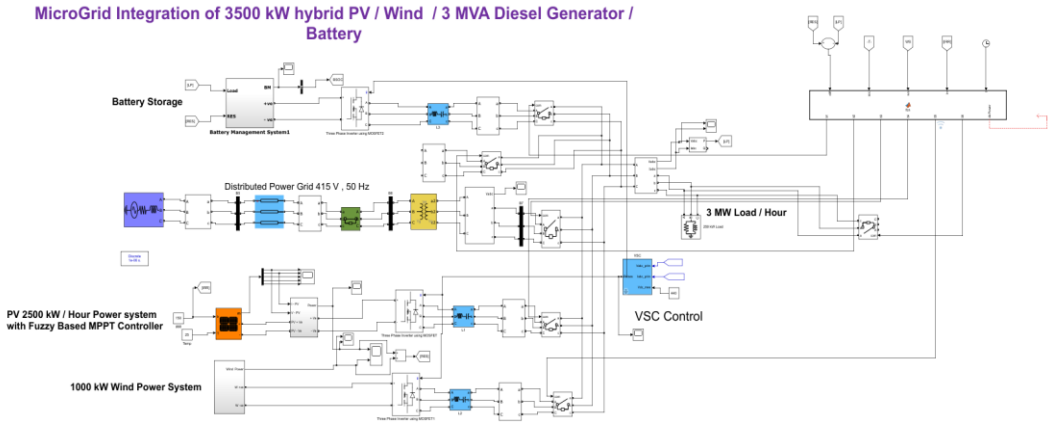

Figure (1): Microgrid of Coastal City.

Using MATLAB Simulink was a logical choice to represent the system in a human Readable way which fits this paper, by using Simulink renewable and control Components it's easier to model, avoiding manual labour and the axis of failures System is designed at high voltage to reduce the current and the losses in the circuit

2.1. Material Components of System

1. Battery storage system
2. Grid integration
3. PV sub-System with MPPT optimisation
4. Wind turbine subsystem with MPPT optimisation
5. VSC control & MATLAB Function (Arduino Control) & AI

1. Battery Storage System
   Battery is Rated at 440V and 3000Ah size. A fuzzy logic controller was implemented to determine charging and discharging actions of the battery. Compared to PID or logic-based controllers, fuzzy logic provides superior adaptability and decision-making under uncertainty, especially in hybrid energy systems.
2. Bi- Directional Converter is used in Grid integration as in Figure (2).
3. PV Subsystem – 2500 kW / hour with Fuzzy MPPT is used as in Figure (3).

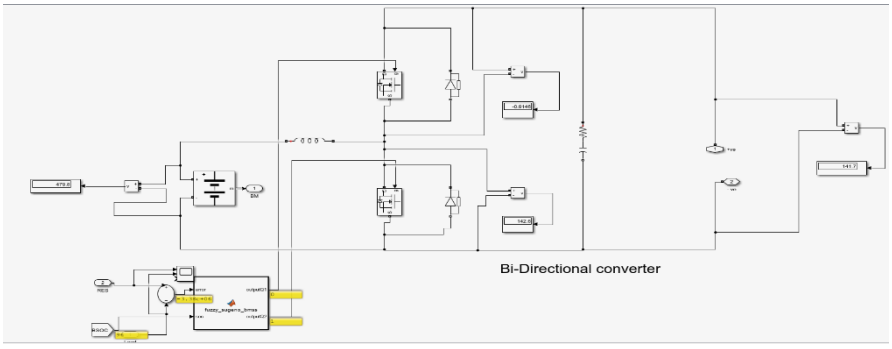

Figure (2): Bi- Directional Converter is used

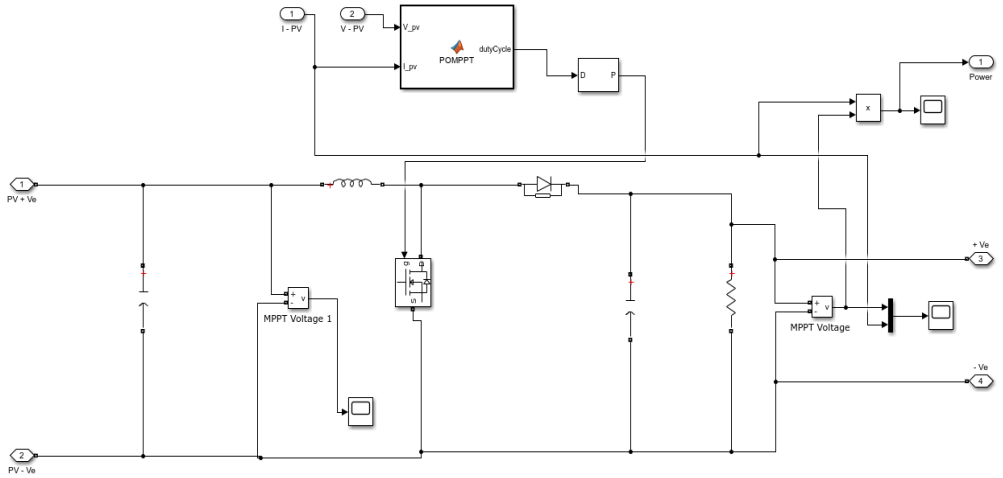

Figure (3) PV Subsystem 2500KW

Based on local solar irradiance data, this size supports daytime load and battery charging in the research, the PV System is equipped with fuzzy logic–based MPPT to maintain maximum power delivery during dynamic conditions.

4. The P&O method is a widely used MPPT technique that works by:
   - Perturbing (changing) the operating voltage or duty cycle slightly.
   - Observing the resulting change in output power.
   - Deciding whether to continue in the same direction or reverse, based on whether power increased or decreased.
5. VSC (Voltage Source control) is high Advanced Control which can measure the voltage and current instantaneously for Adding the different power resources which MATLAB Function choose according to the stored code relative to the environment feature.

Maximum Power Point Tracking (MPPT) is a control loop which search one maximum power point from photo voltaic (PV) array power input, by varying the fraction between the voltage and current delivered to detect the maximum power. Presently, there are so many MPPT algorithm techniques have been modified by the researchers to have an increase the accuracy. Among that, the classical and very easy simulation MPPT algorithm is perturb and observe (P&O) algorithm. On the other hand, the robust and intelligent way of control the MPPT for the PV is Fuzzy logic algorithm. the basic operation and the design steps of the above two algorithms may be illustrated with MATLAB/Simulink simulation and its performance data will be compared at different solar radiation and temperature [10].

The inputs to the Fuzzy Logic controller are changed in PV array Power (ΔP_{PV}) and changed in PV array current (ΔI_{PV}) corresponding to the two sampling time instants for analysing the real data of electrical grid. The two inputs are controlled by the Fuzzy Logic controller and the output of the Fuzzy controller is the incremental reference current (ΔI_{ref}). The output of main generation is oriented to the Dc-Dc power converter. The input variable (ΔP_{pv}) for the Fuzzy Logic controller is divided into seven Fuzzy sets referring to the application needed [10].

Variable speed wind generator systems must be controlled to detect the maximum available power from the wind and so to increase the amount of captured energy [11].

Thea maximum power point tracking (MPPT) strategy is very important in Design for a variable speed wind, small scale, wind turbine systems based on a fuzzy logic controller (FLC). The FLC has as input variables the

change in mechanical power (ΔP_m), the change in rotor speed ($\Delta\omega$), and the sign of $\Delta P_m/\Delta\omega$. The change of reference generator current (ΔI^*) is the output variable. For small power applications, when the turbine inertia is relatively small, and the wind speed changes continuously, it is important to consider the transients to develop an accurate theoretical model and to attain optimal operation. Therefore, the mechanical power (*Pm*) is composed of the generator mechanical (input) power (*Pg*) plus the dynamic power, resulting in the dynamic power versus rotating speed curve. The controller can track the maximum power point for changing wind conditions and is robust with respect to turbine parameter changes. The FLC is described, analysed and validated by digital simulations [11].

The PV system consists of a PV panel, DC/DC Buck-Boost converter with a 24V DC load, and a fuzzy logic controller to create high-efficiency photovoltaic system (PV) with a fuzzy logic controller. Because the efficiency of normal solar PV modules is very low, the fuzzy logic controller is added in the proposed system that is designed and simulated in MATLAB Simulink to get good performance. This controller can facilitate the PV array to reach the MPPT faster and support more stable output power [12].

Creating a Simulink model capable of scaling and monitoring renewable source using MATLAB help in simulate the microgrid system with its condition.

Critical Zone Factor which affects renewable resources

- The PV array is modeled to produce up to 2500 kW/hour based on irradiance input (IRR) and system characteristics.
- Regulates power using MPPT (Maximum Power Point Tracking).
- Tracks the Maximum Power Point (MPP) using Fuzzy logic controller of the PV system using the Perturb & Observe (P&O) algorithm.
- Adjusts the duty cycle sent to the DC-DC converter from 0-1 to control the boost converter to maintain MPP.
- Wind Power System is controlled with (MPP) using Fuzzy logic controller at the same time with PV array.

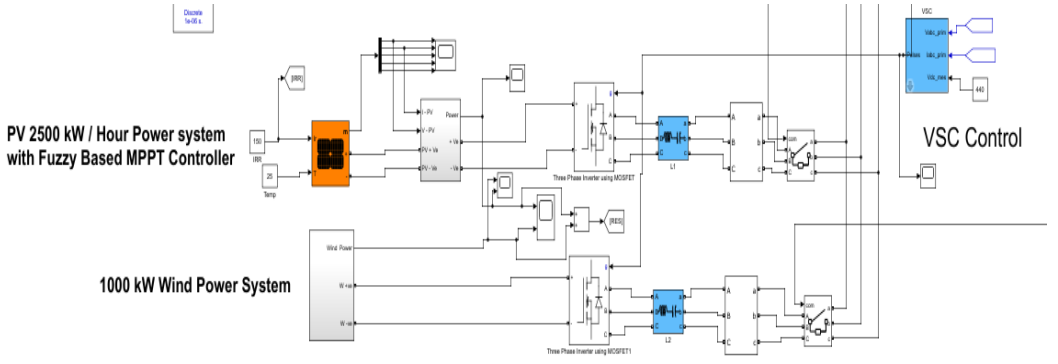

Figure (4): PV Array with Wind power system with VSC based on Fuzzy MPPT Controller

Wind Turbine Converts kinetic wind energy into mechanical rotational energy which is transferred to electrical using different components such as Induction Generator, Rectifier (AC → DC) and Sensor Inputs

Wind speed (WS) affects turbine speed and power output and the Speed-Torque curve influences mechanical performance. MPPT for Wind – Torque-Speed Logic is used when Wind Speed (WS) and Rotor Speed (ω) as in Figure (5).

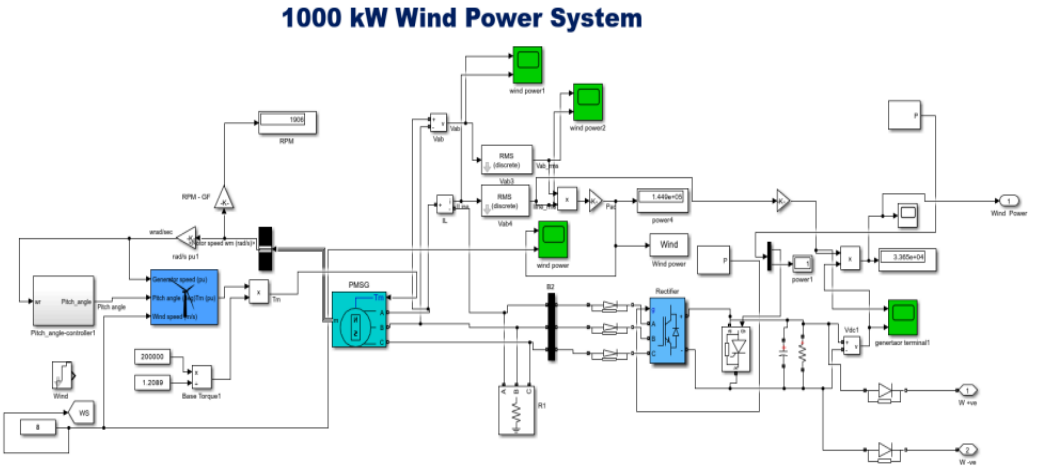

Figure (5): MPPT Logic for Wind Genera

In the research the Main Operation Modes to satisfy the load of Coastal City are suggested as the following:

1. ideal mode (PV + wind +Grid + Battery)
2. Surplus (PV + Wind + Battery or Emergency Generator) diverting power
3. Night mode /winter (Wind + Battery + Grid)
4. Low wind /Summer (PV + Battery or Emergency Generator + Grid)
5. Renewables fault (Grid + Battery)

Operation Mode is coded in the truth table to illustrate the system under different real-life conditions simulating the appropriate response and triggering breakers to handle them

b1: Battery,
b2: surplus divert
B3: grid
b4: PV Module
b5: Wind Generation
b6: Fault and connect Generation to Load.

AI Technique

The Luxury Life of Coastal city depends on the continuity of Electrical feeding for city therefor, the management of different resources such as PV Array, Wind turbine system, Emergency Generator and Electrical Grid are controlled by MATLAB function (Arduino) Automatically according to the Feature of environment (wind speed, irradiance of sun and validity of battery). The proposed MATLAB function (Arduino) is designed with the truth table with the Forbidden Zone due to the limit of irradiance and Wind speed in Ain Sokhna Site to enhance the loading of Coastal city.

The proposed MATLAB function (Arduino) of Figure (6) has output of generated Function to connect the resources to the load by switching CB to connect the generation with load according to the truth table in Table (1). The system performance is oriented to operate the coastal city with energy enhancement around the different Season of year by assuming the worst operation condition around the year as peck loading in summer, loading at winter and Disturbance of Resources (operation modes) which is taken in consider in truth table with forbidden zones due to the environment of Ain Sokhna City.

The forbidden zones of environment are summarized due to the irradiance (irr) in range from zero to 1000 [13], and the wind speed (WS) which is considered an input parameter for the generated MATLAB Function, for example (winter mode), the sun is set at the night and the PV Array is out of duty and the wind turbine with the grid will be available and also the battery will be ready when it is charged. The resultant Power Generated from renewable resources (RESLT) is the sum of PV Power and Wind Power which is compared with Load

Power Dmand (LP) to determinate the situation of the required power to satisfy the load by inserting the battery or emergency generation or the charged battery. The difference between (RESULT) and (LP) is defined (diff) which is found in Figure (1) and Figure (6) which is considered input parameter for the generated MATLAB Function. The PV design simulation test results using MPPT P&O and Boost Converter depend on the predetermined radiation. With the maximum amount of radiation, the PV Array produces a maximum power as practical experiment in the research [13].

battery state-of-charge (BSOC), which is considered input parameter for the generated MATLAB function is very important to the Battery to indicate the ability to insert in the duty in the range from 35% up to 95%). When the battery charge is less than 35%, the battery is advised to charging to get charged battery at the peak energy time.

The Validity of wind speed affects the output of Wind turbine. When the Wind speed is smaller than 5 m/s, the wind turbine is preferred in the out of duty mode [14], The wind speed in the site of red sea of Egypt records from 4.4 m/sec up to 5.8 m/sec as practical studies [15] which can help the sustainable studies. The Truth Table includes ten different operation cases to simulate the environmental features to enhance the load demand at any time around the year.

VSC (Voltage Source control) is high Advanced Control which can measure the voltage and current instantaneously for Adding the different power resources to feed the load demand as in Figure (4) with the following power conditions:

a) Ensure synchronization with the grid
b) Provide feedback for control (voltage, frequency, and power quality) Acts as the core inverter of the system.
c) Ensures that battery or PV power can feed into 3-phase AC loads or the grid.

Table (1): Truth table of Schedule Control

case	diff	soc	irr	ws	b1	b2	b3	b4	b5	b6
1	> 0	< 95	> 0	>= 5	0	0	0	1	1	0
2	>0	>= 95	> 0	>= 5	0	1	0	1	1	0
3	< 0	>35	> 0	>= 5	1	0	1	1	1	0
4	< 0	<= 35	> 0	>= 5	0	0	1	1	1	
5	> 0	>=95	= 0	< 5	0	1	1	0	0	0
6	<-1e5	>35	= 0	< 5	1	0	1	0	0	0
7	= 0	35 -95	= 0	< 5	0	0	1	0	0	1
8	> 0	>= 95	= 0	< 5	0	1	1	0	0	0
9	> 0	< 95	= 0	< 5	0	0	1	0	0	1
10	< 0	<35	= 0	< 5	0	0	0	0	0	1

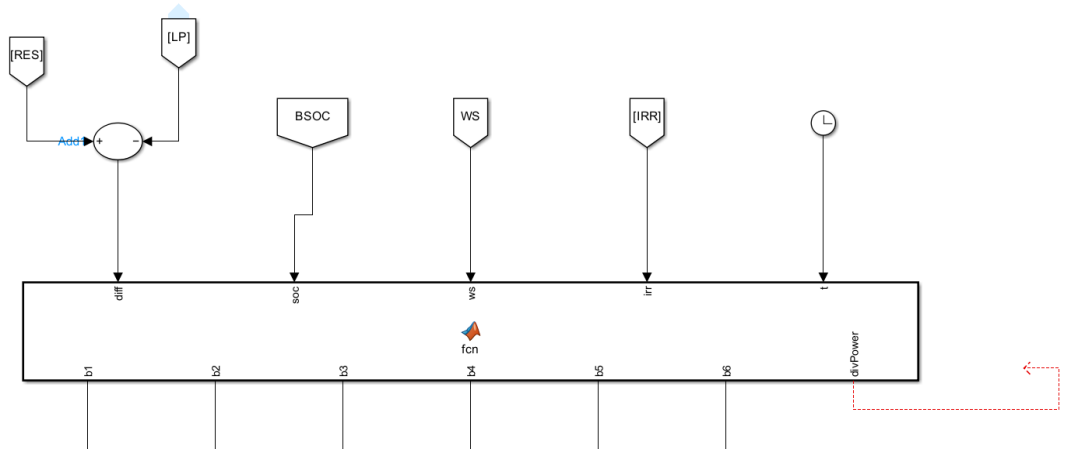

Figure (6): Generated function with truth table as Scheduler Circuit & logic (Arduino)

Results:

The AI Technique of the proposed generated MATLAB Function create the stability of the renewable resources Energy to satisfy the load demand around the year and also detect the main situation of each renewable System individual by sensing the main parameter as the wind speed (WS) for wind turbine periodically and Irradiance (Irr) for PV Array and the total output power to recognize the ability to feeding the load power. The ability of PV Array and Wind turbine is compared with Load power automatically (diff) to take decision with inserting the help with Battery module when it is charged or with Gird and Emergency Generation which is coded in the statement of generated MATLAB Function from the conditions of the truth table.

The Truth Table includes ten different operation cases to simulate the environmental features to enhance the load demand at any time around the year and the practical condition of the renewable resources (Forbidden Condition of renewable System). The management of the different renewable resources to operate in the same time and synchronized with zero shift in time domain is referred to VSC Control. VSC Control keep the quality of load output because the synchronization isn't affected by grid turning on and of which results in a smoother output as in Figure (7).

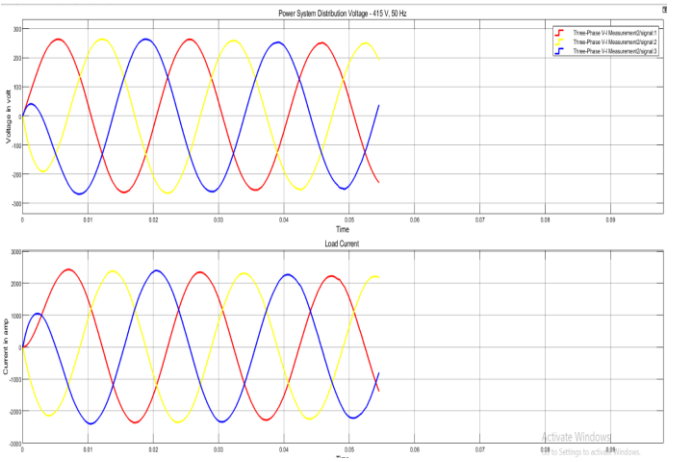

Figure (7): The output at load under tuning the PV Array and Wind System in Microgrid

The Coast City is supported with intelligent AI technique to satisfy the load demand at different real life around the year in fifth Operation mode as the following:

1. ideal mode (PV + wind +Grid + Battery)

In this case the load of coastal City is supplied from the renewable resources PV Array, Wind Turbine Farm with Battery y Storge together with the small enhancement of Grid at critical peak situation to compensate the huge of required power when the Irr = 1000 , Battery full , WS = 10 optimal to simulate the maximum power generated to Load as in Figure (8).

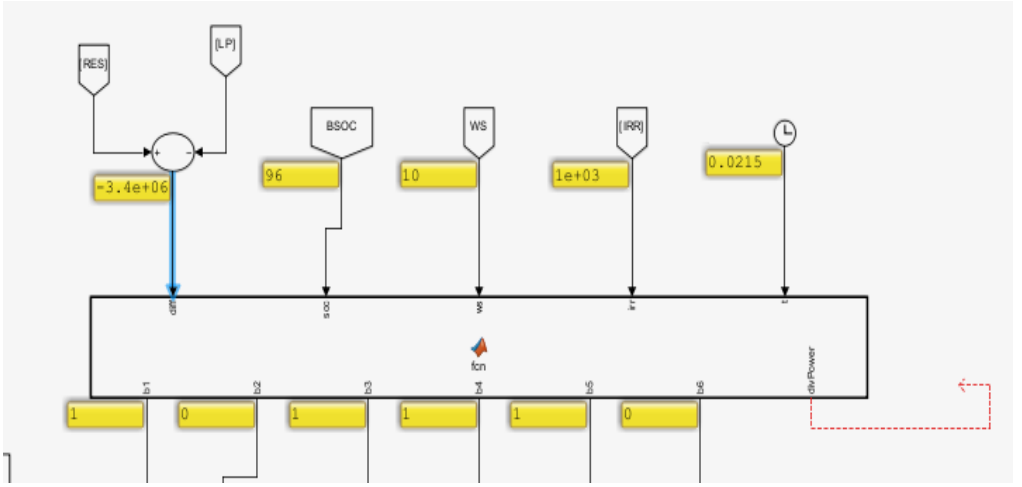

Figure (8): the maximum out power discission of MATLAB generated Function

2. Surplus (PV + Wind + Battery or Emergency Generator) diverting power

In this case the load of coastal City is supplied from the renewable resources PV Array, Wind Turbine Farm with Emergency Generator only to satisfy the required power as in Figure (9)

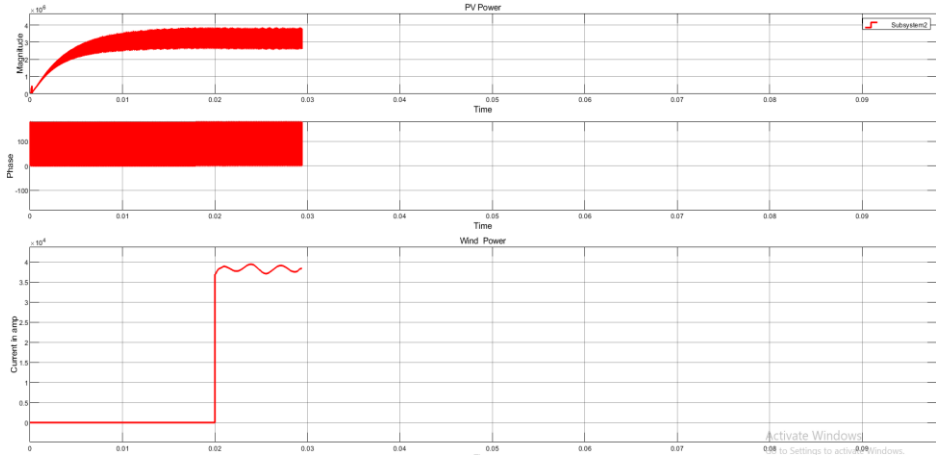

Figure (9): The response of PV Array and Wind energy which controlled with VSC to satisfy the load

3. Night mode /winter (Wind + Battery + Grid)

In this case the load of coastal City is supplied from the renewable resources Wind Turbine Farm with Battery Storge together with the small enhancement of Grid to compensate the Absence of PV Array due to the night day mode or the winter weather when the Irr = 0 , Battery full , WS = 10 optimal to simulate the environment weather at delivering the power to Load as in Figure (10.a).and Figure(10.b) represents the response of power and load current after synchronizing with VSC.

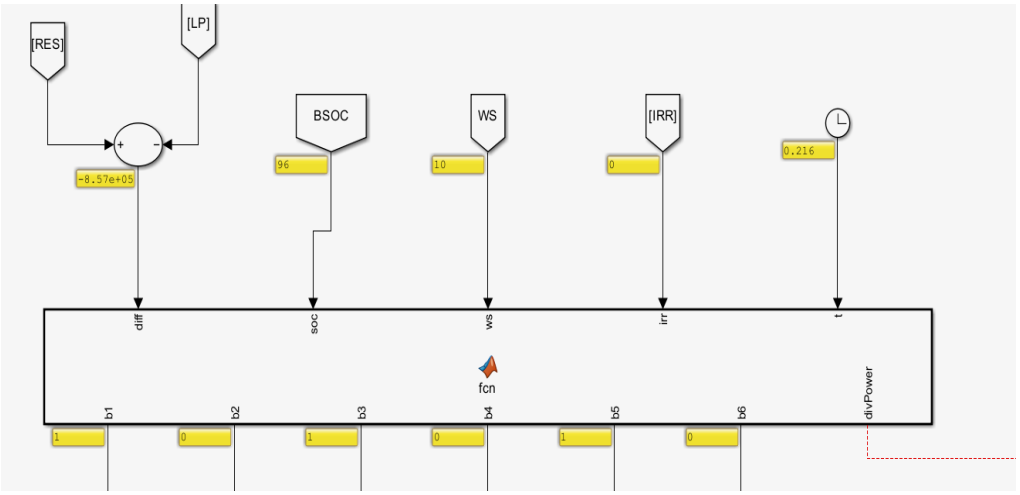

Figure (10.a): Night mode or winter weather mode at feeding the load demand

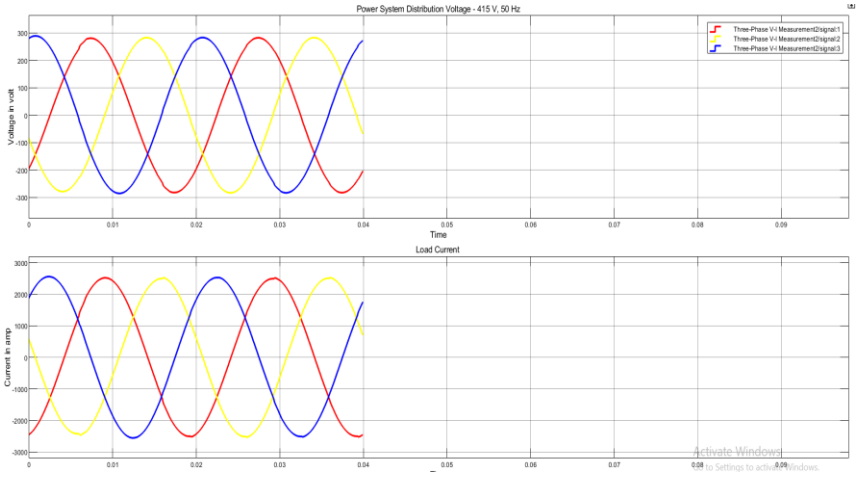

Figure (10.b): The output response of power and load current at Night mode /winter Weather

4. Low wind /Summer (PV + Battery or Emergency Generator + Grid)

In this case the load of coastal City is feed from the renewable resources PV Array with Battery Storge or Emergency Generator as in Figure (14) in the Absence of Wind turbine Farm when the Irr =1000 , Battery out off duty , WS = 0 to simulate the Summer environment weather at delivering the power to Load as in Figure (11.a) and Figure(11.b) which represents the response of power and load current after synchronizing with VSC between the PV Array and Emergency Generator.

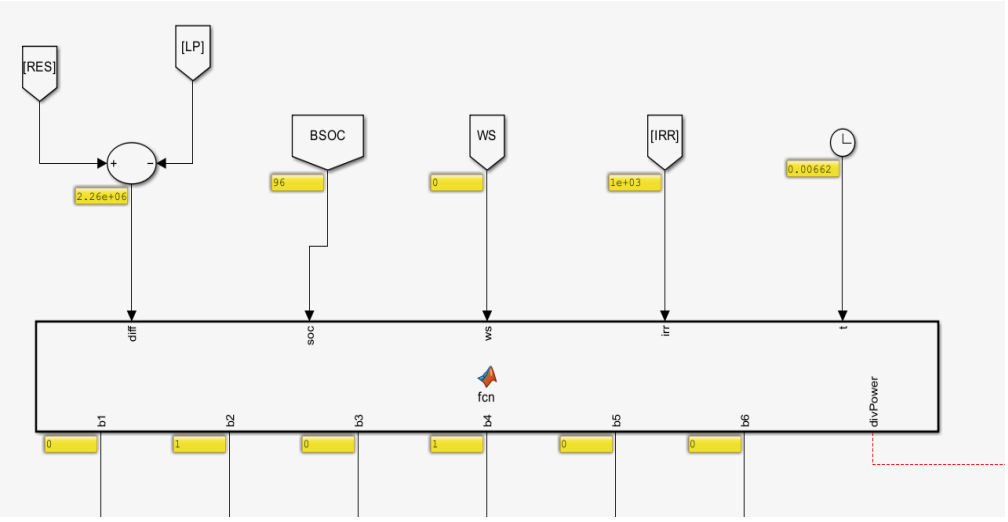

Figure (11.a): the suggested mode of summer weather mode at feeding the load demand

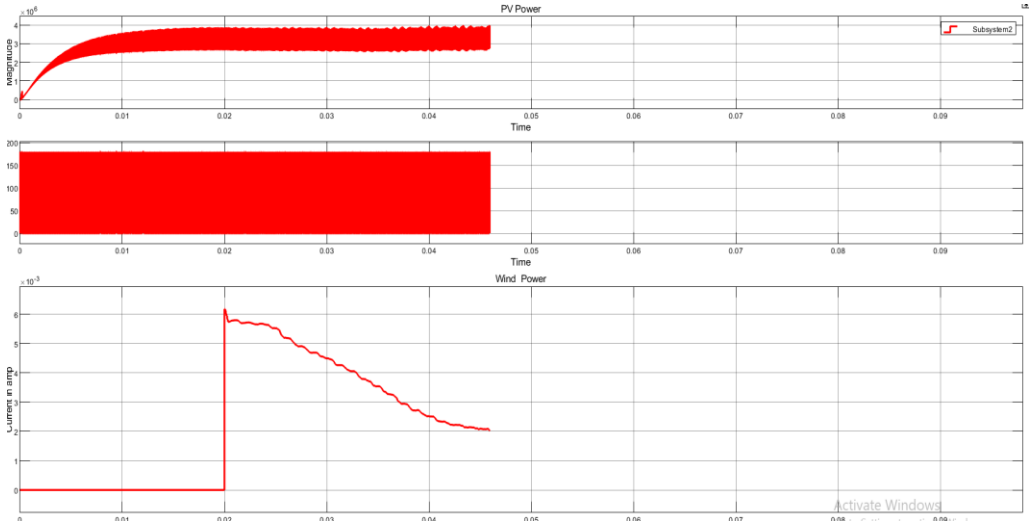

Figure (11.b): The output response of power and load current at Summer Weather Basic on PV Array

5. Renewables fault (Grid + Battery)

In the worst condition, the renewable resources of PV Array and Wind turbine Farm may be is out of duty which is sensed by (diff) input of the proposed MATLAB Generated Function which choose the grid and Battery charged to feed the load demand of coastal city as follows:

a) At the instant of the failure of renewable resources Energy, the load of coastal city is supplied from the grid and the battery when in good state as 95% maximum as in figure (12.a).

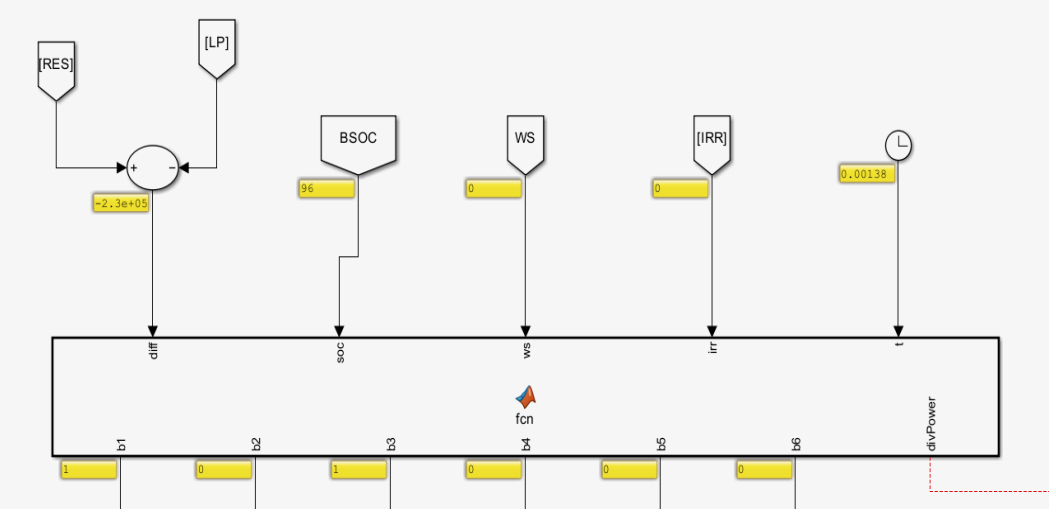

Figure (12.a): The Absence of Renewable resources in feeding the load demand

b) if the battery is drained and b6 will trigger notifying that no renewable source is available and the load is supplied from the grid only to compensate for the failure of renewable resources Energy as in Figure (12.b).

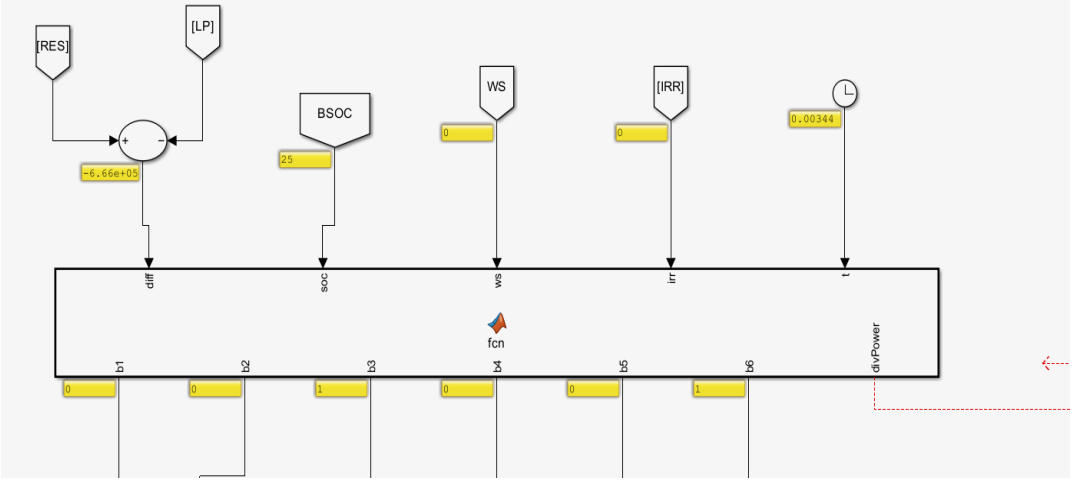

Figure (12.b): The feeding of Electrical Grid in the worst condition

Discussion

the renewable resources are controlled and oriented with AI Technology enhancement (MATLAB Generated Function) to simulate the forecasted operation situation according to the environment weather with the ability of different renewable resources for achieving the success of feeding the energy for load demand of coastal city with suitable sustainable conditions and economical Automatically at long run. AI technology with the suggested (MATLAB Generated Function) is very effective in operation only but is not help in maintenance process. In this research, the AI technique insure the continuity of energy feeding for load demand of coastal city when the renewable resources in duty with healthy equipment's.

Conclusion

The Electrical system of Coastal City is modified to involve different renewable resources with electrical grids to achieve the continuity of electricity using Fuzy logic controller for MPP of the PV array and Wind Generation at different mode which depends on the behavior of Coastal environment around the year. The suggested Microgrid discuss the hybrid energy control system with Smart logic handles multiple energy conditions to reduces blackout risk and the Battery play essential role in the stability of Energy management.

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