A Review of Hybrid Renewable Energy Systems and MPPT Methods

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Abstract- In the last years, there are several studies and researches in the literature about hybrid and Maximum Power Point Tracking (MPPT) Methods have been performed to obtain efficient systems. Hybrid systems uses renewable energy sources and features of these sources have to be known to apply suitably. In this article, the mentioned renewable energy sources, MPPT methods and hybrid systems are explained and the review results are given with tables and also, MPPT and the hybrid systems are compared.

Keywords-- Maximum power point tracking, renewable energy, hybrid systems, fuel cell, photovoltaic panel, thermoelectric generator, diesel generator, wind turbine, hydroelectric power station, biomass based power generator, piezoelectric

Nomenclature

MPPT	: Maximum Power Point Tracking
PV	: Photovoltaic Panels
STC	: Standard Test Conditions
PEM	: Polymer Electrolyte Membrane
TEG	: Thermoelectrical Generator
N.M.	: Not Mentioned
HOMER.	: Hypergeometric Optimization of Multiple Energy Resources

1. Introduction

Human have been tried to find new ways, tools and technologies to get easier their lives in all their life. During time, the technological and technical development is an example of this phenomenon and the life is getting better, but the number of tasks is getting increase. This incrementation represent new jobs which wanted to experience. The main requirements for the tasks are energy, electrical etc. [1]. Wei numerically analyzed the Molten Carbonate Fuel cell system. The examination related to a project that aim is to get dynamic model and control of 1MW Molten Carbonate Fuel Cell System [2]. Following years, another study was performed by Sera et al. In that study, single diode modelling of Photovoltaic (PV) panels at Standard Test Conditions (STC) was explored. The proposed model uses only five parameters on the data sheet and the results shown that the proposed model was agreed the parameters of datasheet data [3]. The other research was done by Ural and Gencoglu in 2010. The topic was the Polymer Electrolyte Membrane (PEM) Fuel Cell. The PEM fuel cell was efficient and it would use hydrogen as fuel and the aim was to obtain mathematical model of PEM Fuel Cell. Dynamic model of the PEM Fuel cell investigated using MATLAB/Simulink [4]. Mboumboue and Njomo presented an article that focused on Mathematical modelling and simulation of PV Panel using MATLAB. While the inputs of proposed model were sun irradiation and cell temperature, outputs were output current and voltage [5]. The other paper aimed to obtain mathematical model of wind turbine and the

researchers used two different methods [6]. Ozdemir and Mutlubas examined the biodiesel production and they focused to obtain alternative fuel supply by the diesel generators. The biodiesel's CO_2 emission was non. However, it produces NO_x gasses [7]. Another article examined the Thermoelectrical Generator (TEG) Device. The working principles which Seebeck Effect, Peltier Effect, Thomson Effect, and Joule Effect were defined. Structural analyses were done. And theoretical model was obtained. [8]. Other paper searched the TEG devices applications. The main phenomenon of the working principle of TEG device was examined. Design and optimization studies were done and well-designed models achieved [9]. One research was performed about the Piezoelectric Material for harvesting electrical energy from the piezoelectric crystals. The aim was to obtain maximum energy production. Three different renewable energy sources were studied as wind power, wave power, and thermal power [10]. Ataol prepared a thesis that examine the TEG's efficiency under close geometric areas which had hot air flows. Thesis also present the coefficients of Seeback, Peltier, and Thomson effects and energy generation's related conditions [11]. In an article, renewable sources were researched detailly. The renewable energy sources were classified and determined, such as solar energy has two title photovoltaic technology and solar thermal energy [12].

1.1. MPPT Techniques

Onat and Ersoz presented a study that compare MPPT Algorithms. These algorithms were Perturb & Observe Algorithm, Constant Voltage and Current Algorithm, Incremental Conductance algorithm, Parasitic Capacitance Algorithm. The results show that most efficient one is Parasitic Capacitance [13]. Caliskan prepared a thesis that examine the PV systems for DSP based sun inverter design. In that study, MPPT methods were also mentioned as Open Circuit Voltage and Short Circuit Current Method, perturb and Observe Method, Incremental Conductance method and their comparison [14]. Dris and Djilani written a paper that research the Perturb & Observe, Incremental Conductance and Fractional Open Circuit Voltage methods. Under Cloudy weather most efficient algorithm was Incremental Conductance Method, but it requires more sensor than Perturb & Observe algorithm [15]. Another MPPT related study was performed by Erdogan et al. In the paper, highly efficient MPPT method design for PV panel was studied. The aim was to reduce switching losses for that reason Soft Switching Methods were designed and implemented for the MPPT Methods to obtain high efficiency [16]. In another research, the new MPPT method approach based on incremental conductance algorithm was presented. This method was improved by using incremental conductance, constant voltage and look-up table approach. The results shown that the convergence time is decreased, however this reduction did not affect the voltage and current ripples [17]. The other application done by using Adaptive Fuzzy Logic MPPT controlled under partial shading condition. The result shown that proposed technique was better than other two techniques [18]. Kurak et al. written an article that research PV panel behavior using Buck Converter controlled MPPT Algorithm. Mentioned algorithms were Constant Voltage Algorithm, Incremental Conductance Algorithm, Perturb & Observe Algorithm. The research used Perturb & Observe algorithm to obtain low cost, highly efficient, easy applicable battery charge system [19].

Srikumar and Saibabu presented a study that propose two algorithms of MPPT methods. One of them Incremental Voltage Step Size Algorithm, and other is Adaptive fixed duty cycle algorithm. These methods were implemented under five different conditions. The results shown that tracking efficiency, maximum tracing efficiency, and settling time of the fixed duty cycle algorithm method is better [20]. In a paper, Constant Voltage Tracking, Open Circuit Voltage Tracking, Short Circuit Current Voltage Tracking, Current Scanning Method, Perturb & Observe, Incremental Conductance, Parasitic Capacitance etc. were mentioned. Comparison of these methods are presented [21]. Another review study was about to classify the MPPT Methods [22]. Tozlu, and Calik also prepared a review article about the MPPT techniques. The study classified the MPPT methods as 1st Generation, 2nd Generation and 3rd Generation [23]. Celikel, and Gundogdu studied a comparison article that compare Perturb and Observe algorithm and Incremental Conductance algorithms for using Field Programmable Gate Arrays [24].

1.2. Hybrid Renewable Energy Systems

Lloret et al. presented a paper that examine PV-thermal hybrid application systems. This goal of these applications was to reduce CO_2 emission with using renewable energy sources and from using similar applications on public buildings to reduce the area related costs of PV panel systems [25]. Zakharchenko et al. performed a study about PV/thermal system which the PV panel's crystalline type was different. The aim was to obtain high electrical and thermal efficient system [26]. Yu and Yuvarajan researched the PV and PEM Fuel Cells based hybrid system load sharing principles. From using PI controller, the system tried to maintain balanced under demanded load. The

system used PV panel for maximum power as available as possible [27]. Obara prepared a study that use the PEM Fuel Cell and Wind Turbine based hybrid system to reduce energy cost and greenhouse gas emissions. The results shown the behavior of the systems and condition that increase the power generation efficiency [28]. Hrayshat studied techno-economic analysis of the Wind-Diesel generator systems under several hour run simulation according to Jordanian's villages remote load demand [29].

Shaahid and El-Amin performed an application that electrify PV-diesel system in Saudi Arabia for off grid system. Techno-economic examination also researched and the PV penetration on the whole system was also mentioned. The result shown that diesel efficiency was increased, and diesel usage was decreased [30]. Brent and Rogers presented an article that research wind-solar system in South Africa and the economical, sustainable system was examined [31]. Liu et al. studied about a new DC Micro-grid system. In this system, PV and wind sources connected to grid. As load, electrical vehicles contain storage components as batteries and ultracapacitor were used. It explored under four operation mode and validity was shown according to results [32]. Palizban et al. examined the behavior of hybrid system which contain wind Turbine, PEM Fuel Cell, PV, and another element like electrolyzer, super capacitor. The result shown that the efficiency was been as desired under different conditions (different application and different renewable energy sources) [33]. Yamagueu et al. written a paper about PV diesel without battery unit and off grid areas. The diesel generators operation was between 70-80% (optimal point) and it was efficient under high load and high solar radiation [34]. Altanneh presented a thesis that the topic was charging of electrical cars battery by using PV and Hydrogen Fuel Cell [35]. Another study was a feasibility study by Bekele and Tadesse in 2012. The Hydro, PV and wind powers were used as energy sources in Ethiopia electrification application. In the experiment, the real data were used and HOMER system also used. From the results, the cost of obtained energy was higher than the national tariff [36]. Another analysis was performed for isolated wind PV hybrid system. The result shown that the system was produce more than two laboratories illumination power and the extra produced energy above this demand was stored in the batteries [37]. Vick and Neal prepared a research about wind turbine and PV hybrid energy production for water pumping applications [38]. Dongmei and Yanhua presented a paper about wind and PV sources as a power supply. The aim was to obtain stable operation and smooth switching between grid connected condition and the islanding mode operation. The system was built using DigSILENT Power Factory software. The control was hybrid and the controls were P-Q control and droop control [39]. Goel and Ali prepared a feasibility analysis study of the electrification in Odisha India by using Hybrid energy sources by using HOMER. The aim was to obtain optimize and low-cost system [40]. Rhaman explored hybrid renewable and sustainable energy combination. Different types of hybrid systems were used in the study. The renewable energy penetration was examined (%43). Some places using PV-Diesel and battery combination, the energy cost was reduced and also the CO_2 was decreased [41]. Ammar et al. studied about using thermal and solar power (PV-Thermal hybris system) with using Artificial Neural Network control to obtain optimal power from the sources [42]. Another energy production study was performed by using Solar-Wind-Diesel-Hybrid system for St. Martin Island in Banglades. The optimization was done using HOMER software. The aim was to produce enough energy for 100 households and 10 shops [43]. Maleki and Askarzadeh studied about PV, wind and fuel cell sources (combination of these sources) to find the optimum system. From using Chaotic Search, Harmony Search and Simulated Annealing techniques, the PV-fuel cell, wind-fuel cell and PV-wind-fuel cell combinations, optimum configuration was obtained. The results shown that three sources combined hybrid system's cost was minimal [44]. Nour and Rohani presented an article about using PV and diesel hybrid system to produce electricity for western region of Abu Dhabi. The HOMER device used for determined hybrid system. PV panels energy penetration was about 27% and the CO_2 emission was decreased about 23% with using only diesel generator [45].

PV-Diesel hybrid system for oil producing communities in Nigeria was explored in another study. The optimization was done using HOMER according to Net Present Cost. The aim was to obtain efficient, reliable, cost-effective system [46]. The other article was performed with using PV and fuel cell and ultra-capacitors. The main aim was to track load demand power and compensate sudden power changes [47]. Hakimizad et al. collected information about renewable energy topic and current implementations. The aim was to supply the lightning systems, small electronics devices, producing hot water, heating and cooling the Urban Parks in Tehran, to increase energy efficiency from using renewable energy [48]. Ozden presented a thesis about PEM-fuel cell performance under solar hydrogen renewable hybrid system application. The main aim was to produce electrical energy for emergency room. The PEM was modelled using

ANSYS Fluent and data from TRNSYS model [49]. Another thesis presented by Alkan was about PV, Wind and Fuel cell sources and produce electrical energy. The aim was to control energy usage, to store energy and to transfer the energy to grid by using smart energy management algorithm. The system verified using MATLAB/Simulink. The result shown that using instantaneous control of energy level, the optimum energy delivery can be obtained. The efficiency was increased, and the energy was saved. This optimization technic reduced the required power value, and also cost [50]. Can presented a thesis about using meta-heuristic method to optimize the microgrid system which contains PV, Wind and Diesel Generator. The aim was to obtain minimum operation cost and optimum power by using genetic algorithm [51]. Rahman et al. written an article about using PV and wind which fed a buck converter. The system tested using MATLAB/Simulink [52]. Ganesan et al. studied about modelling, control and analyze the PV-Wind-PEM Fuel Cell system. The voltage and power of the system should be balanced under different operation mode such as on grid and off grid. The model was designed by using MATLAB/Simulink [53].

Sharma and Suhag presented a study that they proposed a new control mechanism for PV Wind hybrid system to obtain constant DC link voltage without any additional load. The slow response of battery storage was eliminated with supercapacitor [54]. Belkaid et al. written a paper about PV and TEG device connected to boost converter controlled by sliding mode control. The simulation was performed by using MATLAB/Simulink under variable solar radiation system [55]. One paper published that the aim was to review the renewable energy sources. The classification was done with two different titles as operation mode and structure of hybrid systems. Optimization techniques also mentioned [56]. Altun and Kilic studied about the PV-Wind hybrid energy production system. According to this article, the produced energy was enough to compensate 450 households annually. The real data was used for weather conditions between 2011 and 2014 [57]. Yilmaz presented a thesis about wind turbine (asynchrony machine modelling) and PV Panel usage to produce electrical energy and the analysis was performed by using MATLAB [58]. Also, Koyi presented a thesis that tried to combine Nigeria's grid connection with renewable energy sources. The result shown that reliability and resilience of Nigeria could be increased [59]. Latif written a thesis that present micro grid system based on renewable power generation. The proposed system was designed for working under islanded and grid connected conditions. For cost reduction, the 3-phase inverter was used [60]. Mayer et al. presented a paper about PV, wind, solar collector to obtain an optimized system for environmental conditions and economical issue using genetic algorithm. The aim was to obtain household scale system which had multi objective and optimize the system [61]. Another review study was performed by Naz et al. The main objectives were to determine effective cost, find environmentally friendly and produce economical energy. The review also contained hybrid topologies, principles of systems and control methods [62]. Qadir et al. written an article that examine PV-Wind hybrid system under seven different weather conditions by using machine learning models. The article classified the machine learning techniques. The aim was to obtain statistical learning models that train itself. The result shown that linear regression method had better performance [63]. Zebra et al. presented a study that they tried to overcome changing natural conditions of the renewable energy sources. The results shown that the local support on the studies were important to achieve successful integration [64].

Ozdemir studied on his thesis about to examine the hybrid system contains PV, wind, PEM Fuel Cell. Other studied subjects were hybrid systems reliability point, probability distribution of the aggregate power (theoretically). The data were obtained from meteorology station. The results shown that wind speed values were fitted for Weibull distribution, and PV was fitted for Beta distribution. From the results, reliability of the system was approximately 94% [65]. Beyarslan presented a thesis about to design microgrid from using renewable energy sources and optimize the system by using HOMER device. The aim of thesis was to reduce electricity cost and reduce carbon footprint of the villages. The data of the weather was collected and the combinations of the PV, wind, hydroelectric power plant, fuel cells and storage units had used. The HOMER was preferred to optimize the system with the aim of reducing fossil fuel usage, using the different types of renewable energy sources and the storage units [66]. Mumcu et al. studied about to use piezoelectric material to produce electrical energy. Piezoelectric device would generate electricity by wind, rain, waves, light etc. [10].

From the review of the hybrid system, we understand the importance of the hybrid systems. Moreover, there are many studies have been performed to examine hybrid systems. The sources topics are; Wind-Hydro hybrid system [67], PV-TEG [68-69], hydro-PV-diesel [70], wind-PV [71] , different combinations [72-75].

2. Renewable Energy Sources

Table 1. Review table of renewable energy sources		
Name of Source	**Explanation of the sources**	**Reference Sources**
Photovoltaic Panel (PV)	PV panels are device that has P-N junction surfaces and using solar radiation and sun light to produce electricity in the model. There is one controlled current source, one diode and two different connected resistance. According to [12], there are ways that convert solar energy to electrical energy.	[1], [3] ,[5], [12]
Fuel Cell	Fuel Cell Devices uses chemical energy to produce electrical energy there are several (from [76] 7) types of Fuel Cell devices. In the mathematical equation, there are one voltage source, 2 different connected resistance and one capacitor.	[1-2], [4], [12], [76]
Piezoelectric	Piezoelectric Material for harvesting electrical energy from the piezoelectric crystals. It will harvest energy from wind and wave energy also.	[10]
Thermoelectrical Generator	The TEG Device works for using Seeback, Peltier and Thomson effects, and also Joule Heating Principles. The equivalent Circuit has one controlled voltage source and one resistance.	[1], [8-9], [11]
Biodiesel	Diesel generators are use fossil fuel sources as an input and produce electricity as an output, however some diesel generators will design or updated that using biodiesel source to produce electricity. The new system uses biological sources as a fuel. [12]	[1], [7], [12]
Wind	The device that using wind flow produce electricity is Wind Turbines.	[1], [6]
Hydroelectric Power Station	The waters potential energy is used as a source energy, and using this energy the Hydroelectric power stations produce electrical energy.	[1]

3. MPPT Review Study

Table 2. Review table of MPPT methods		
Name of MPPT Methods	**Detailly explanation**	**Related sources**
Constant Voltage Tracking, Open Circuit Voltage Tracking	This is based on the ratio of MPPT voltage and Open Circuit Voltage of PV panel and it changes between 71%-80%. Optimally, 76% is used.	[13-15], [19], [21-23]
Constant Current, Short Circuit Current	This is based on the ratio of MPPT Current and Short Circuit Current of PV panel it changes between 78%-92%. Optimally, 86% is used.	[13-14], [21-23]
Perturb & Observe, Hill Climbing	• If the PV Voltage is increasing the power change is positive, next step is PV Voltage increase. • If the PV Voltage is increasing the power change is negative, next step is PV Voltage decrease. • If the PV Voltage is decreased the power change is positive, next step is PV Voltage decreased. • If the PV Voltage is decreased the power change is negative, next step is PV Voltage increased.	[13], [15], [19], [21-22] Comparison study [24]
Incremental Conductance	In this method relationship with delta current and delta voltage ratio and minus current divided by voltage is	[13-15], [19], [21-23] Improved Method

	important $\frac{\Delta I}{\Delta V} = -\frac{I}{V}$ at Maximum Power Point (1) $\frac{\Delta I}{\Delta V} < -\frac{I}{V}$ to the right of the Maximum Power Point (2) $\frac{\Delta I}{\Delta V} > -\frac{I}{V}$ to the left of the Maximum Power Point (2)	[17] Comparison study [24]
Soft Start Techniques with MPPT	In one research, the soft start techniques are used with MPPT techniques for reducing switching losses	[16]
Parasitic Capacitance	The parasitic Capacitance method is like Incremental Conductance, but the P-N junctions' parasitic capacitance is important in this method.	[13], [21-23]
Direct Control Methods	Ripple Correlation Control, Power Feedback, Photovoltaic Array Combination, Actual Measurement is another Direct Control Methods according to [21]. From article PV's sampled data is used for these methods.	[21]
Sliding Mode Control	This method is based on sliding surface and it has also higher order methods	[21]
Array Reconfiguration	According to [21] these methods based on switch, sensors and controllers' changes. These methods are; Simple Series, Series Parallel, Bridge Link, Total Cross Tied	[21]
Combine Methods	In the articles, some researches use more than one MPPT algorithm to obtain more efficient systems such as; Particle Swarm Optimization Perturb & Observe, Fuzzy logic Perturb and Observe, Artificial Neural Network Incremental Conductance.	[21] Application [18]
Artificial Intelligent Techniques	The artificial intelligent is new, but an interesting topic. In the renewable energy applications, some research uses these methods. These methods are; Particle Swarm Optimization, Artificial Bee Colony Algorithm, Slap Swarm Algorithm, Gray Wolf Optimizer, Genetic Algorithm, Fuzzy Logic Controller, Artificial Neural Network, Differential evolution,	[21-23] Application [18]
New algorithm-based comparison	In one article Incremental voltage step size algorithm (IVSSA), and Adaptive fixed duty cycle algorithm is compared with each other	[20]

4. Hybrid System Review Study

Table 3. Review table of hybrid systems

Name of Hybrid System	Detailly explanation	Efficiency (System, Source, Cost of the articles summary)	Used MPPT Techniques	Reference
PV- TEG	In this type of hybrid system research some of them application research that examine efficiency. One research is examined energy economic issues	Given intervals 99.6%-70% system efficiency, 14.88% Source efficiency, %25 from without cooling system.	Artificial intelligent, Sliding mode control, others N.M.	[1], [25-26], [42], [55], [68-69]
PV- Fuel Cell	In this type of examinations are focuses on these topics: Load Sharing, optimization of the system, system efficiency, and source efficiency	90% system efficiency, 11.2% fixed angle PV, %50 PV and %50 Fuel Cell	Constant Voltage with PI, other N.M.	[1], [27], [35], [47], [49]
Wind- Fuel Cell	A micro grid application is found in the literature	N.M.	N.M.	[1], [28]
Wind- Diesel Generator	In an off-grid examination is found for Jordanian settlements.	72% wind penetration	N.M.	[1], [29]
PV- Diesel Generator	There are four researches that examines the energy penetration and efficiency of the system.	70-97% system efficiency and 27% PV panel energy penetration.	N.M.	[1], [30], [34], [45-46]
Wind- PV	There are 15 research that examine this topic. System efficiency and energy penetration	85-100% system efficiency, 38.8 Solar Panel efficiency, other N.M.	Artificial Neural Network, P-Q control, PI and PR control, other N.M.	[1], [31-32], [37-39], [48], [52], [54], [57-61], [63], [71]
Wind- PV- Fuel Cell	There are 4 studies about the renewable hybrid study. The system efficiency.	94-100% system efficiency,	Weibull distribution, Beta distribution	[1], [33], [50], [53], [65]
Wind- PV- Hydroelectric Power Station	One research searches the energy penetration.	%90 renewable energy of demanded power	N.M.	[1], [36]
Wind- PV- Diesel Generator	There are 3 different study about this topic.	%90 system efficiency	N.M.	[1], [43], [51], [70]
Wind- Hydroelectric Power Station	The optimum configuration is examined.	N.M.	N.M.	[1], [67]
Piezoelectric TEG	In the research	N.M	N.M.	[10]

	Piezoelectric material is used for obtain electrical energy from using wind and wave energy. And the hybrid system is examined.			
Combine studies and Review studies	These types of studies have more than one hybrid model and they are compered in the researches.	More than one research	More than one research	[1], [40-41], [44], [56], [62], [64], [66], [72-75]

5. Conclusion

In this study, the importance of Hybrid system, the hybrid system control methods and MPPT technics are highlighted. In the literature there are several sources that examine individual renewable sources, examine Hybrid systems, and also examine MPPT techniques. The obtained sources are explored and become together to obtain summary information. We believe that from using this information, the renewable energy studies are increased with the development of semiconductor technologies, software and new devices.

Acknowledgements

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