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Review Article

A Review of Hybrid Power Generation: Modelling-Simulation, Control Strategy and Future Trend Development

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Abstract

Hybrid power generation is one of the most discussed topics in power engineering society nowadays. It is due to the characteristics of participated power sources are different including the variable input parameters and fluctuation of load demand. Therefore, the main challenges in hybrid system are to find the optimal performance, sizing and configuration for the target of minimum operational cost, maximum efficiency and reliability and reduction of carbon gas emission within the pre-determined constrains. This paper attempts to reveal the typical modelling and simulation procedures, control strategy and future trend development of hybrid power generation. The study yields that the utilization of Hybrid Optimization Model for Electric Renewable (HOMER) software dominates the simulation procedure to obtain the optimum technical, socio-economic and environmental performance of hybrid systems. In this respect, there have been ambitious plans to maximize the potential solar energy with other back-up energy sources to supply the electricity energy demand worldwide. In addition, the variety of control strategy has been implemented to take the advantages utilization of hybrid power generation. In the end, the future trend development is mainly focused on the increase the optimal performance of hybrid system based solar thermal power or other thermal engine systems combined with different types of generating systems.

Keywords: hybrid power generation, modeling system, software simulation, control strategy, hybrid thermal systems.

1. Introduction

Hybrid power generation is defined as the combinational operation between the renewable and non-renewable energy resources or between the renewable and non-conventional energy resources including the utilization of energy storage systems. In this respect, the non-renewable or conventional power generation is characterized with the most well-known typical power generation in practices with the controllable output electric power, such as hydro power, oil and gas-based engine power generation. Meanwhile, the renewable energy resources are sometimes referred to non-conventional power generation types, such as photovoltaic (PV) systems, wind power and so on where their output power are characterized with uncontrollably, variably and high dependency on environmental conditions. Meanwhile, the non-conventional energy resources are termed to thermal systems-based engine generation which not widely known and implemented, such as fuel cell, hydrogen energy and other derivation of solar thermal energy utilization. Because different types of power generation are elaborated together in a single system, the hybrid power generation is remained being attracted to be investigated in order to find the optimal performance within certain challenges and constraints.

The most common practice of hybrid power generation is in a remote area or in an isolated island. In such area, the electrification is the main problem because of the location is far away from the main electricity grid. The utility is reluctant to extend the transmission lines due to high cost investment while the returned value of investment is relatively low. The solution for the electrification is to supply the area using diesel generator. The diesel machine is considered to be able to provide electricity supply and to shave the load customers which are characterized with slow variations except the load profile changes significantly between day and night times. It means that the electricity is supplied only at night by the diesel machine, while no electricity activity during day time. However, there are problem operations of diesel engine power generation, such as continuity of fuel supply, oil price and carbon gas emission. The fuel supply is sometimes delayed due to transportation and weather problems especially when the location is completely difficult being accessed. The oil cost is another problem where the price tends to increase recently, while the carbon gas emission is the most considerable side effect of burning oil to produce electricity using diesel engine. All it all, the diesel generator has enormous technical and environmental impacts.

The feasibility study of hybrid power generation in isolated community regarding the engineering, environmental and economic aspects under specific conditions is proposed to solve the global financial problems and greenhouse gas emission. The study focuses on the technical and economic feasibility of replacing diesel engine with different combination of hybrid systems [1]. In fact, the diesel generator has significant technical and environmental considerations [2]. Meanwhile, the utilization of various configuration of hybrid power generation by means the inclusion of PV system and wind energy may have important gain on engineering and economic feasibility in order to meet the electricity demand.

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In this respect, the model development of optimal control performance of hybrid system-based PV and diesel generator might be designed for the minimization of daily cost of electricity [3]. Also, the real-time experimental benchmark for stand-alone hybrid wind and diesel power with battery systems is performed with the main tasks to improve the behavior of overall systems [4].

The hybrid power of solar and wind energy systems is comprehensively discussed from the innovation in advanced technology approach and control strategy for the global perception and pattern utilization [5]. The connection of hybrid generation has important issues on reliability of grid systems. Even though the variability output of wind-solar hybrid systems, the islanding operation is negligible. Therefore, the islanding detection is also a vital issue for distributed generation integration [6]. The optimal combination of such hybrid power generation systems is able to meet the annual load and to minimize the total annual cost to the customers [7]. In this respect, the optimal configuration is presented by the feasibility analysis for input policy of renewable implementation. The purpose of the study is to improve the reliability performance and minimizing the energy storage requirement during the low wind speed condition [8]. In comparison through the experimental study, the PV and wind power contribute as the primary and secondary energy supply, respectively to the load energy share [9].

The solution of optimal power management for standalone hybrid power generation is commonly investigated. The method is to clarify the changes and dynamics of the uncertainty condition to the optimal solutions [10]. In remote location, the provision of stand-alone hybrid generation is often more effectively in terms of generation cost than connected to the power grid. When several type of power sources combination exist, the control strategy of power dispatch is highly important for the economic operation and long-term utilization of hybrid systems [11]. An example, the standalone hybrid power generation based solar energy is used for the electrification of rural area. In this case, the optimal energy production of combined power generation is prompted to eliminate the drawbacks of other types of generation systems [12]. In addition, the implementation of hybrid power systems in isolated island increases the energy security and promotes the economy and environment perception on green power generation [13].

The energy sources in remote area are characterized abundance which mostly from renewable energy with high promising potentials to be used as electricity energy sources. For instance, the sunlight intensity is normally higher than other locations with longer sun duration. The wind speed is feasible to rotate the blade of wind power. The potential of hydro power for mini- and micro-hydro power generation is constantly available through the year. If the technology is provided for these types of energy sources, then the operation may combine with diesel engine to supply electric power to local customers. The electricity from the solar panel is stored in battery systems during the day and being used during the night time. The wind blows almost every time so that the loads may receive electricity no only at night but just during the day. The hydro power may suppress the output of diesel generator significantly in case of water capacity is more enough, while the load capacity is less enough. In this regard, with the availability of renewable power generation in remote location, the diesel engine is only used to peak-shave the load profiles especially when the load growth demand is gradually increased.

The hybrid combination between the hydro power source with other types renewable power generation has given significance of technical consideration. With the PV systems, it might be impossible due to the high capital cost investment of both power generations [14]. However, an approach to allow this hybrid system to be cost-effective is to utilize the water reservoir and battery banks as the storage energy systems to suppress the complementary characteristic of both power generation types. The theoretical concept is to determine the limit of plants performance within the idealized energy availability function. The high capacity of solar energy in grid connection makes the intermittent power and system frequency that leads to the decrease in power quality [15]. The combination of solar energy with hydro power improves the power quality by means taking the benefits of complimentary output characteristics. The proposed method is intended to maximize the net revenue during lifetime operation in order to meet the optimal sizing of PV system capacity.

The smooth operation, clean and energy efficiency of power generation are the challenges to be solved by the combination between conventional and renewable energy source aided by energy storage components. The scheduling model regarding to effective operation strategy of hybrid power generation is developed with the target of optimum fuel utilization, minimum emission within the fulfilment of energy demand [16]. In this respect, the integrated power generation-based energy storage system may improve the overall efficiency and increase the fuel saving ratio [17]. The configuration of hybrid wind-hydrogen and storage energy system may overcome the low supply-demand and discrete wind speed characteristics. In this case, the energy flow diagram and system performance are presented for the proposed strategy to compare the different option of hybrid configuration [18]. However, to some extents the operation of hybrid power generation-based storage energy hydrogen is quite complex [19]. Therefore, it is important to have generic and flexible decision-making model for the hybrid management strategy in order to achieve good performance when connecting different power sources to energy storage systems.

The proposed hybrid system may also eliminate the battery utilization and environmentally adaptive under partial load operation and could be the best operation strategy when the economic and environmental aspects are fairly considered. For instance, the PV home system is normally installed in remote area with difficult access to the grid connection. However, significant number of this system is not properly function or not working at all due to substandard equipment, lack of user awareness, inability to maintain their systems, as well as the nonexistence of after sales services. Consequently, it impacts to the battery disposal which is danger potentials to the environment. Implementation of hybrid systems of PV-wind power may reduce significantly the battery disposal without effecting the load demand [20].

The hybrid power system contributes for the significant generating capacity. The share information and experience are to increase the capacity between renewable energy, to improve the hybrid concept of renewable energy/energy storage device and to utilize the micro grid systems with variety connection of power sources [21]. In this case, the strategy of hybrid energy system-based PV, micro-gas turbine and tri-generation (power-heating-cooling) system is presented to obtain the economic and environmental performance by means the life cost analysis and actual emission, respectively [22]. Another name of hybrid power generation is the poly-generation when the energy utilization from different power sources end up in the customers' side in the form of electricity, heating-

cooling and desalination [23]. The generating systems is capable to overcome the output fluctuation of renewable energy sources, to reduce the cost of generation and to mitigate the carbon gas emission. Also, the energy balance analysis is utilized for preferred energy unit of PV-bio hybrid power unit to realize the self-sustaining high-strength wastewater treatment application [24]. In this respect, the optimal performance of hybrid power generation based reverse osmosis desalination system is modeled and simulated for the minimum operational cost [25]. Also, the performance of hybrid power generation based hydro power and wind energy system is analyzed for energy demand in water treatment plants including the economic analysis of payback period [26].

Variety of power sources combination is approached to take the advantages of hybrid power generation and to obtain the optimal performance criteria. The hybrid renewable based marine and land source availability is investigated and compared for the cost payback and profitability. The optimal land and ship location are the significant factors to decrease the fuel consumption and greenhouse gas emission [27]. In this case, the transportation and installation planning for offshore energy platform is investigated and evaluated for floating hybrid power generation including the expected optimal performance [28]. Also, the optimum sizing-based energy production of stand-alone hybrid power generation systems for marine context application is investigated according to the minimization of overall system costs and carbon emission [29]. An example, the utilization of hybrid power system in ship has attracted more attention, especially the use of solar energy combined with storage energy devices. In this respect, it is essential to have the optimal size of hybrid system within the minimum investment cost and carbon gas reduction [30]. Also, it is important to determine the optimal size of energy storage systems in hybrid system of ship application for the target reductions of fuel cost, investment cost of energy storage equipment, carbon gas emission [31].

The hybrid performance between PV system and fuel cell technology is getting mature and receives significant attention. For instance, the model of hybrid optimization-based PV system and fuel cell for household application is investigated [32]. The target for this optimization is the minimum annual operation cost and carbon gas emission within the reliable operation of hybrid systems. Completed analysis of economic evaluation, natural gas prices, the optimal electric and thermal balances are accounted for the environmental benefits of hybrid power systems based operating scenarios of PV, fuel cell and battery systems [33]. In this case, the hybrid power management strategy including the daily load profile, solar intensity, operation of battery systems and external energy constraints is considering to solve the economic power dispatch problems. Also, the fully automatic performance of hybrid power generation is highly important. Therefore, it is important to determine the optimal size and operation including the overview of technical-economic configuration [34]. In addition, the hybrid stand-alone application is expected to maximize the hybrid power efficiency through the solution of constraints of optimization problems including the increase the heat and power production, and controlling the carbon emission [35].

Recently, the hybrid power generation based solar thermal power system has been attracted to increase the share of solar energy capacity in electricity demand supply. The review of hybrid power generation based concentrated solar thermal with renewable and non-renewable energy sources has been presented. The common perspectives are the reduction of carbon emission, plant characteristics and performance metrics. However, some parameters such as energy efficiency, solar-to-electricity efficiency, capacity factor and cost effectiveness need improvement for the competitive hybrid systems [36]. Therefore, it is important to have integrated analysis in finding the key knowledge regarding the attributes, location, area and shape of renewable energy sources potentials to determine the energy production of hybrid systems [37]. In other perspectives, the research investigates the economic, environmental, and technological feasibility of hybrid systems of grid-connected power systems through the improve energy infrastructure, reliable energy supply and implementation of energy policy [38]. With sensitivity analysis, the grid connected hybrid power systems depends on the input parameters of sunlight intensity, load demand and electricity shortage with considering the present cost of equipment [39].

It has been shown that there were incredible efforts to maximize the potentials utilization of hybrid power generation supplying electricity load either in the stand-alone or grid-connected systems. The targets of these efforts are to find the optimal performance by increasing the power generation capacity with low-cost, to obtain the optimal configuration and sizing of participated hybrid system within specified technical constraints and to take the benefits of socio-economic and environmental aspect from the impacts of hybrid power system utilization. These efforts might be supported from different methods of optimization, modeling and simulation including the control strategy for the best-technical and economic system performances. All these summary points are in presented in the following section and finalized with the future trend of hybrid power generation based different solar energy utilizations.

2. Modelling and Simulation Techniques

The energy demand and climate environmental concerns have driven the potential energy sources forming the hybrid systems. The serious investigating of the all promising renewable energy source yield the mature technology together with economic and environmental advantages. To achieve these goals, the modelling of hybrid system is highly important. For these reasons, the performance of analysis modelling and control design are addressed to reach the optimum output energy [40]. In this case, the performance of battery systems in stand-alone hybrid power generation is simulated taking into account mathematical model of current rate, the charging efficiency, the self-discharge rate, as well as the battery capacity parameters to fulfil the criteria of both complexity and precision of battery model in highly varied operation conditions [41]. In comparison, the mathematical model of solar thermoelectric and PV hybrid systems is solved with Matlab/Simulink software including the design of logic control for the reliable and effective operation of hybrid systems [42].

Modelling in hybrid power generation is highly important to further investigate the behaviour system performance. The hybrid system based renewable energy and coal-fired generation system is presented to for energy conservation and gas emission reduction. The general matrix model of heat energy balance and exergy loses is designed including the investigation of thermo-economic performance, energy conservation and emission reduction potentials [43]. In comparison, the three-dimensional numerical model by finite volume method of hybrid systems of PV and thermoelectric generator (TEG) presented with defined functions is generated to consider the

behaviour of systems [44]. The TEG is installed at the backside of PV module in order to produce much power than single PV generation systems and to avoid unexpected cooling systems performance due to the existence of TEG. In this respect, the implementation of thermal management is necessary where large temperature difference can be achieved in TEG by the control of heat flow by putting copper plate as thermal concentrator and conductor at both sides [45].

The hybrid power generation is getting popular as the alternative energy supply in rural area as the mature of renewable energy utilization and the willingness to reduce the fossil fuel consumption. The study provides the model, design and analysis of hybrid systems considering the improving performance, establishing techniques for accurately predicting output and reliably integrating of renewable energy sources with other conventional generating sources [46]. The design method of hybrid power system is presented based modified electric system cascade analysis taking the power pinch analysis as the guideline development of stand-alone hybrid system [47]. The optimal design based minimum loss of power supply probability and number of storage units is achieved through Matlab/Simulink simulation model and the model performance is compared with HOMER simulation output. In addition, the pinch analysis by means the power pinch analysis is used as the graphical method to find the minimum target of outsourced electricity from hybrid energy systems and to determine the amount of excess energy for storage during start-up and normal operation [48]. This method can be used for decision masking technique and design of hybrid systems.

The renewable hybrid generation system-based wind and solar energy is reviewed from the characteristics of abundance and environmentally friendly. In this respect, the hybrid combination is potentials to solve energy shortage problems and fluctuate oil price. The renewable energy is continuously developed by improving their performance, establishing techniques for accurately predicting their output and reliably integrating them with other conventional generating sources [49]. When solar and wind power are operated independently, they are naturally unstable and totally unreliable. However, the aggregation of both resources could increase the output energy and reduce the power fluctuation. The hybrid power-based wind and solar energy for rooftop installation of residential application is simulated with Digsilent software in terms of voltage profile, voltage imbalance, transformer loading, and curtail dump power of PV-wind power hybrid systems which consider the meteorological data and load demand [50].

Meanwhile, the high accurate static and dynamic model of fuel cell is presented to show the capability of fuel cell to follow the variation of load demand fast. In this case, the hybrid combination of fuel cell with battery system in order to achieve fast energy compensation to follow the dynamic changes of load with also considering to eliminate the destructive harmonics effect [51]. The optimization and simulation of energy conversion process oh stand-alone hybrid power generation-based PV system, fuel cell and battery are performed under Aspen Plus environment software [52]. In this case, the dispatching problem and operational feasibility are solved under different scenario analysis. In other cases, similar software is used to evaluate the performance of near zero carbon emission of hybrid power generation in terms of efficiency energy conversion and balanced integration of each power generation components [53].

All it all, the Matlab software is commonly used to solve the mathematical model in hybrid power generation. The steady-state mathematical model is utilized to simulate different operating condition of fuel cells, such as fuel utilization factor and average current density for the target of electrical and total system efficiency [54]. The information is beneficial as the prior knowledge for the optimal design and optimization of hybrid systems. In this case, the total energy of hybrid systems-based fuel cell and exhaust gas from chiller is presented to provide power, heating and cooling concurrently. Also, numerical simulation of transient performance of hybrid system based concentrating solar thermal and thermoelectric generator is presented under the Matlab Simulink software simulator [55]. The aim of this study is to provide thermal mechanism to increase the efficiency and performance of the hybrid module. In addition, the optimization of the potentials of local energy source in the form of hybrid power systems of micro hydro systems and PV panel is analysed with HOMER and Matlab software based on the availability of water resources and load profiles [56]. The simulation results yield with the largest capacity of micro hydro, it reduces the energy cost and carbon gas emission significantly but high investment cost.

Regarding the modelling and simulation techniques in hybrid power generation systems in [40-56], it is highly important to gain beneficial information according to the software and hardware availability, performance evaluation, validity results, novel aspects and significant achievement. These identified reports are comprehensively summarized in Table 1 as follows.

Table 1. Modelling and simulation techniques in solving hybrid power generation problems

Hybrid systems	Construction design		Performance evaluation		Validity results		Refs.
	Software	Hardware	Analysis	Simulation	Novelty	Significances	
Wind power, solar panels & balance of systems	None (review article)		Fault analysis & management technique	Modelling of real-time system	Supervisory control system & data acquisition	Effective and efficient energy moderation in the near future	[40]
			Modelling systems	Technical performance, accuracy & reliability	Trend hybrid power systems	Technical feasibility & competitiveness	[46]
			Design, operation and control of PV-wind power	Improve performance, accuracy & reliability	Future potential development	Economic attractiveness and user's acceptance	[49]

	None (modelling approach)	Telecommunication relay station	Current rate, charging efficiency, self-discharge rate & battery capacity	Mathematical approach of lead–acid battery behaviours	Statistical analysis & probability distributions	Battery working states in real hybrid system	[41]
	Matlab/Simulink & HOMER	Real system in Oujda city	Modified electric system cascade	Optimal design algorithm	Power pinch analysis	Promising costs of energy	[47]
	DIgSILENT PowerFactory	LV network with 74 residential homes through 10 mini-pillar connections.	Optimal design under unbalanced three-phase voltage	Voltage profile, voltage imbalance, transformer loading & curtail dump power	Low voltage residential energy utilization	Optimal & suitable combination of PV-wind power capacities	[50]
PV- thermo-electric- systems	Matlab software	None (modelling approach)	Sub-systems and energy of hydrogen storage tank	Mathematical model of hybrid systems	Design of logic control systems	Reliable & effective solar hybrid system	[42]
			Heat sink with water-media fluid	Numerical simulation approach	Harvesting heat loss & improved efficiency performance	Transient performance of CPV-TEG	[55]
	None (modelling approach)		Electrical and thermal behaviours	TEG modules & optical concentration ratios	Homogeneous medium & finite volume method-	Concentration ratio with heat sink characteristics	[44]
	ANSYS with finite element method	Thermal concentrated PV-TE systems	Heat flow & temperature distribution	Thermal management	Copper plate concentrator	High efficiency in absence of sunlight & economic feasibility	[45]
RE with coal-fired power generation	Matlab software	None (modelling approach)	General matrix models heat balance & exergy losses	Thermo-economic performance, energy conservation & emission reduction potentials	High increments of thermal performance & critical energy conservation potential.	Improved thermo-economic performance indicators with increasing shunt coefficient	[43]
Hybrid RE systems	None (modelling approach)		Power pinch analysis	Optimal networks for recovery and conservation of resources	Management of storage systems	Hybrid power system design	[48]
Fuel cell & battery systems	PROTEUS and MATLAB environments	None (modelling approach)	Dynamic response of fuel cells & cost analysis	Dynamic model of fuel cells	Elimination of harmful harmonics	Fast dynamic response	[51]
PV-fuel cell & battery systems	Aspen Plus environment	None (modelling approach	Dispatching & operational feasibility	Power dispatch & fuel cell performance	New design & analysis urine-to-hydrogen processor	Battery compensation for energy gap	[52]

Solar hybrid systems		GRAZ integrating solar heat systems	Exergy efficiency & carbon capture	Solar heat conversion & performance parameters	Near zero carbon emission	Complementary utilization of fossil fuel & solar heat	[53]
Hybrid Solid oxide fuel cell	Matlab software	SOFC & absorption chiller	Fuel utilization factor and average current density	Steady-state mathematical model	Electrical & cooling efficiencies	Design & optimization of total energy system	[54]
PV - micro hydro plant (MHP)	Matlab software & HOMER	None (modelling approach)	Energy cost, emission reduction & RE	Different capacity of MHP	Trade-off capital cost & system capacity	Maximum performance of power plant	[56]

In comparison, HOMER software is the most dominating computer software program to solve the optimization problems in hybrid power generation (Table 2). The Hybrid Optimization Model for Electric Renewables (HOMER) software is utilized as a tool for the technical and economic feasibility of stand-alone hybrid systems such as biogas, PV, Diesel Generator, WT and battery systems. The simulation results indicate significant contribution of the hybrid parts, potential of reducing carbon emission and alternative economic option for electrifying the remote area. In general, the technical and economic feasibility of off-grid hybrid power generation can be investigated for the rural area application with this software tool [57]. The analyse of hybrid power generation for rural application is performed to obtain the optimal energy efficient and the optimal location-based cost-effective configuration. Similarly, the software is used to perform technical and economic feasibility of hybrid system considering net present cost, initial capital cost and cost of energy as economic parameters [58].

The feasibility study of hybrid power generation is investigated according to the minimum cost of energy to supply the load demand. The HOMER software has capacity as a tool to measure the sensitivity analysis regarding the technical and economic systems feasibility [59]. Also, it gives benefits to investigate the optimal configuration of hybrid system regarding the effect sensitivity of total net present cost and cost of energy to environment [60]. The HOMER simulation tool is utilized to evaluate the technical and economical operation and feasibility of hybrid systems based solar and wind power generation [61]. Global environmental perceptions and increase in electricity energy demand triggered the utilization of hybrid power generation with some portions of renewable energy sources. Similarly, the hybrid power generation based solar panel and wind power for remote area application is carried out according to the net present value and considering the sensitivity variables, such as wind speed, irradiance, solar panel and diesel costs [62].

In other applications, the HOMER software package is used to evaluate the techno-economic performance of off-grid and on-grid hybrid systems of diesel generator, PV, wind and battery systems for large electricity demand. The target of simulation is the optimal configuration based the comparison analysis of technical, economical, and environmental aspects. In addition, the yearly demand growth and government policy is taken into account as the influenced parameters for renewable energy project, carbon tax and electricity price [63]. Similarly, the optimal planning model of hybrid power generation-based PV, diesel generator and battery systems is simulated to meet the real load demand. The discussion of optimal planning is focused on the technical, economic and environmental aspects of hybrid systems including the fluctuation fuel price and economic prospects of hybrid power [64]. Meanwhile, the hybrid systems-based wind power and biogas engine for the standalone application is investigated with HOMER software. The simulation is focused on the technical and economic analysis, such as the optimal values of levelized cost of electricity, capital cost and net present cost in comparison with the independent operation of diesel generator [65].

The techno-economic feasibility of stand-alone hybrid systems for the target zero emission is presented with HOMER software simulation tool considering incident solar radiation, wind speed, electrical demand profile, and equipment characteristics. The optimal economic results from the simulation is measured with total net present cost and cost of energy considering the inflation rate. The sensitivity analysis is also performed to show the correlation between the economical parameters [66]. For instance, the feasibility of off-grid connection hybrid systems is applied for the hotel energy supply. The optimization tool is taken regarding the economic assessment including the sensitivity analysis of input parameters in hybrid systems to the cost and efficiency system performance [67]. Also, the hybrid systems for the telecommunication load in remote area is investigated with HOMER software for the target of efficient energy utilization of renewable energy sources based on technical and economic analysis [68]. Similarly, the simulation of optimal hybrid power generation in hospital building service for the techno-economic performance is simulated with this software. The optimal targets are total net present cost, levelized cost of energy, renewable fraction, excess energy production and the pollutant gas emission of the system. In addition, the sensitivity analysis is taken for the diesel fuel cost and yearly interest rate for the overall system performance [69].

The hybrid system for rural area electrification is presented to reduce the cost and environmental side effects of diesel generator. The high cost operation could be from fuel transportation and fuel price fluctuation. The role of diesel generator can be replaced from different types of renewable energy. For these reasons, the feasibility study is taken with HOMER software for the optimal net present cost and cost of energy. In this case, the study focuses on the operational strategy and sensitivity analysis of the hybrid system for optimal performance [70]. The hybrid combination between the solar energy and diesel energy has been the prominent option to solve the problem of energy shortage due to the depletion of fossil fuel energy sources and promoting clean energy schemes [71]. The HOMER software is utilized to investigate the level cost of energy in different hybrid configuration with

attention is focused on the unmet load, excess electricity generation, fuel savings and reduction in carbon emissions. In remote application, the design, simulation and analysis of hybrid power based solar or wind with diesel generator is presented for the optimal and feasible energy utilization and reducing the total system cost [72].

The technical and economic feasibility of grid-connected hybrid power generation for local area is investigated with variety of renewable energy generation. The optimization technique is carried out with HOMER simulation and sensitivity analysis for the robustness and cost-effectiveness of hybrid micro-grid systems [73]. An example, the hybrid operation is investigated for desalination process and to satisfy the electricity energy demand with considering the techno-economic analysis [74]. Also, the hybrid power system based fixed and sun tracking facilities of PV system and micro wind systems is analysed to obtain the optimum configuration and to improve the power generation potentials. Comparative analysis of different configuration is simulated using HOMER software in order to achieve the improved cost of energy [75]. In other cases, the potentials of hybrid power generation by means the diesel generator, tidal power and PV system including storage devices has been discussed to mitigate the electricity shortages. Similar software is used to analyse the technical and economic aspects for certain output capacity and the proposed system is compared with other systems of the same capacity [76].

Lastly, analysing and modelling performance of standalone hybrid power generation is presented for optimal management, operation and sizing of overall systems using demand response programming. In this case, the management strategy-based demand response and potentials of energy reduction is applied to reduce the imbalance between the generation capability and power consumption behaviour. The HOMER software is used as a tool for optimization program including the GAMS software through CPLEX solver [77]. In this case, the modelling of micro-grid system-based hybrid power generation with biogas and wind/solar energy is presented to mitigate the environmental effects. The method of energy hubs is used for different power source integration to satisfy the different energy production scenarios including the payback cost analysis [78]. Also, the integrating of different power generation in rural area eliminate the concern of oil price fluctuation and the ineffective cost solution for grid connection. The economic feasibility of different energy sources is simulated for the optimal solution of fuel consumption and carbon gas emission including the optimal size configuration [79].

Table 2. Summary HOMER software utilization in hybrid power generations

Hybrid systems	Hardware Design	Performance evaluation		Validity results		Refs.
		Analysis	Simulation	Novelty	Significances	
Stand-alone: biogas, PV, DG, WT & battery systems	Biogas genera (9kW), PV modules (10kW), 2 DGs (10kW each), wind turbine (1kW), 72 batteries (390Ah each) & inverters (15kW)	Technical & economic feasibility	Cost of Energy (COE) & total Net Present Cost (NPC)	Potential reduction in Carbon emission	Economic option of power supply in remote area	[57]
PV, wind power & battery systems	PV (3kW), 2 wind turbines (2.6kW) & 18 batteries with no DG		COE of RE sources	Load demand of a typical residential house & carbon emissions limitation	Carbon emissions reduction in detail for single house	[61]
Standalone: PV, Wind power, DG, biogas engine & battery systems	Wind power (10kW), DG (1kW), battery (1156Ah), converter (1kW), PV (1kW) & biogas engine (1kW)		LCOE & NPC	Biogas engine is better solution than DG as power backup	Lower carbon emission with biogas engine as backup power	[65]
PV, DG, tidal power & battery systems	PV (5kW), tidal-hydropower (8.21kW), battery 20 (1156Ah each) DG-1 (10kW), DG-2 (5kW), inverter (10kW), rectifier (10kW)		Model of possible small hybrid power generation system	Economic viability & technical aspects	Analysis of overall system cost	[76]
Remote area: PV & wind power	None (simulated hybrid systems)	NPV & sensitivity variables	Design and simulation of standalone hybrid power systems	Net present cost of generators	Sensitivity variables & optimization process	[62]

PV, DG, wind power & battery systems	PV (1000kW), DG (800kW), wind power (60kW) & battery (130kWh)	Technical, economic & environmental aspects	COE and RE fractions	Annual load growth & governmental energy policies	Low interest loan to RE projects, carbon tax & grid electricity price	[63]
PV, DG, fuel cell & battery systems	Optimal capacity of different configuration of hybrid systems		Optimal planning of hybrid systems	Replacing battery system with fuel cells	Fuel price fluctuation on the economic competitiveness	[64]
PV & DG	PV (4kWp), DG (10kW) & battery storage of 3 h of autonomy connection	Techno-economic feasibility	COE & operational hours of DG	Effect of battery connection	Un-met load, excess electricity generation, fuel savings & carbon emissions reduction	[71]
PV/wind power with DG & battery systems	PV (15kW), wind turbine (3kW) converter (6kW), DG (2.6kW), ATM (57.8kW) & battery (3000Ah)	Optimal feasible energy utilization & total system cost	Optimal solution for energy supply	Design, simulation and analysis of hybrid system for ATM application	Maximum RE with minimum cost	[72]
PV/wind power, biogas & battery systems	PV (no power specification), CHP (8000kW), wind power (3000kW) & battery (3000kW)	Energy production scenarios, economic, sustainability gains & payback analysis	Energy Hubs methodology: micro-grid operation	Novel micro-grid structure	Integration of hybrid systems of sugar cane plants	[78]

3. Control Strategy

The utilization of conventional control combined with advanced control methods as in Table 3 is still one of the main options of the parameters control strategy in hybrid power generation. The time domain operation of stand-alone hybrid power generation-based wind power, wave energy and compressed air energy storage for remote island service is presented. The simulation results yield that the power-load supply is stable in terms of power and frequency with optimal PI controller [80]. Another approach, the automatic frequency control of hybrid power systems is presented in the corridor of real output power balance systems. The control schemes are the PID and PD controller to keep the zero-frequency deviation and to damp frequency oscillation, respectively [81]. In this study, the sensitivity analysis and control strategy are evaluated to maintain the frequency performance of hybrid systems. Meanwhile, the robust control for hybrid power generation-based fuel cell and supercapacitor is achieved through the control strategy combination between PI and H infinity controls implemented for DC-DC converter [82]. In this research, the optimization method tries to solve Linear Matrix Inequalities regarding parameters of frequency and time performance. In addition, the three-dimensional PID controller is designed and applied for the dynamic control stability of frequency and power variation of wind power in hybrid power generation [83]. The controller parameters are optimized with dragonfly algorithm and compared with the meta-heuristic algorithm for tuning parameters in terms of convergence rate, minimum fitness value and dynamic system performance.

The control of hybrid power generation for household application is presented with the rule-based control strategy considering the optimal system design and sizing and overall energy performance [84]. The rule base strategy is potentials to be deployed for the purpose cost reduction and components lifetime increase in hybrid systems. In accordance, the nearly zero energy for building is investigated in terms of design and control regarding the energy saving, indoor thermal comfort and accommodative environment and grid connection. Since the problems is complex with parameters and high expected performance, the optimization methods are required to deal with system sensitivity, uncertainty parameters for the optimal system reliability, efficiency and optimal control of hybrid power generation and energy storage systems [85]. For these reasons, it requires the predictive control for smart and fast response control technologies.

Design of economic supervisory predictive control-based Hardware in the Loop framework for management of hybrid power generation has been developed to deal with some optimal criteria, such as environmental aspects, fuel, energy and storage costs for solar panels, gas micro-turbine and storage units [86]. For short time prediction, the system performs better storage energy control and power management. Similar method in terms of ultra-short time prediction is designed based on weighted moving average filtering for real time variability of power compensation. In this case, the smoothing control of hybrid power generation called pre-plan power curve is presented based module scheduling, grid limitation of power fluctuation, maximizing output of wind and solar power, reduced operation energy storage systems [87]. Meanwhile, adaptive control for frequency and voltage of off-grid hybrid wind-diesel system is proposed based on constrained linear model predictive control [88]. Frequency and voltage control performance can be achieved the field voltage and rotational speed of synchronous generator. Meanwhile, the proposed controller response based on the minimum cost function of voltage and rotor speed errors within the given constraints.

The review of inverter utilization in hybrid power generation is presented in terms of topology front-end interface, energy conversion stages, the control circuit regarding the stabilization, tolerance and system ageing [89]. In this case, novel voltage control algorithm is developed for the stand-alone hybrid power systems through the control technique in pulse width modulation inverter [90]. The proposed controller is presented in real time digital simulator and satisfied with the balanced and unbalanced load conditions. Similarly, design and evaluation of control system for hybrid power generation scheme is presented. The real time control is aimed to maximize the energy efficiency and electrical power management of hybrid systems base fuel cell [91].

For the utilization of MPPT control performance in hybrid power system, the universal tracker is evaluated to solve the problem of individual controller which are explicitly complicates the system implementation, increases cost, and decreases the accuracy of the MPPT process [92]. The proposed controller may extract high output power, no need for the sophisticated sensors, high efficiency performance and fast time convergence. It is due to the independent MPPT controller for hybrid PV system and fuel cell may give the complicated system structure and creates additional cost [93]. The fast convergence and high accuracy control performance is presented for the hybrid PV-fuel cell systems. In other approaches, the unified MPPT control algorithm is proposed for the hybrid wind power and fuel cell [94]. The proposed method is perfect because no need of sensors, high efficiency performance and fast time convergence.

Table 3. Summary of control strategy

Hybrid Systems	Control strategies	Control operation	Control parameters	Refs.
Wind power, wave energy & compressed air energy storage	GWO & PI controller	Stabilization of power & frequency	Frequency deviation, Power of Compressed Air Energy Storage System (CAES) & net power generation	[80]
Wind power DG, fuel-cell & aqua-electrolyzer	PID & PD controller	Zero-frequency deviation & damping frequency oscillation	Real power balance of DG	[81]
Fuel cell & supercapacitor	PI & H infinity controls	Robust control	Multivariable PI control with H_∞ performance; H_∞ full & reduced order controllers	[82]
Wind power-based hybrid power generation	Three-dimensional PID controller & dragonfly algorithm	Dynamic control stability of frequency & power variation	Time-varying step load perturbation & random wind power perturbation	[83]
PV, DG, battery systems & hydrogen fuel cell	Rule-based control strategy (Hardware-In-Loop test)	Cost reduction, components lifetime increase & energy efficiency -vs- correct system sizing	Optimal design, sizing & energy performance	[84]
Hybrid power generation in integrated buildings	Predictive control based nZEB	Design & control of buildings performance -- fast responses to smart grid & advanced smart technologies	Building performance parameters	[85]
Solar panels, gas micro-turbine & storage units	Supervisory predictive control	Management of hybrid renewable energy system	Optimal criterion of environmental condition, fuel, energy delivery & storage costs	[86]
Wind, solar power & energy storage systems (grid connection)	Pre-plan power curve based smoothing control	Reduced maximum powers fluctuation, maximizing wind-solar power utilization & reducing use of battery energy storage system	Real-time power fluctuation	[87]
Off-grid hybrid wind-diesel system	Constrained linear model predictive control	Adaptive control for frequency & voltage	Field voltage & rotational speed of DG	[88]
Stand-alone; wind, solar power, battery & fuel cell	Novel voltage control algorithm	Optimal inverter utilization	Line voltage at PCC	[90]
Hybrid systems-based fuel cell	Real time novel control algorithm	Maximum energy efficiency & power management	Common DC bus through intermediary electronic converters	[91]
	Universal tracker algorithm	Optimal MPPT control performance	Output voltages and currents of hybrid system components	[92]
Hybrid wind power & fuel cell	Unified tracker algorithm		Electrical power of wind energy systems	[94]

Wind turbine, electrolyzer & fuel cell	Multi-loop nonlinear predictive control framework	Dynamic modelling & control of fuel cell outputs	Stack temperature & oxygen excess ratio	[95]
Hybrid wind & battery systems	Robust tracking controller	Stabilization control due to the wind & load fluctuation	Power quality-smooth transition of frequency	[97]
Hybrid power based micro generation systems	Homeostatic regulation & supervisory control	Operational aspect of micro-generation	Power supply & demand towards efficient system equilibrium	[98]
Grid-connected PV & battery systems	Optimal control method & model predictive control	Scheduling power flow under minimum generation cost & dispatching real-time power flow under disturbance condition	Electricity cost - number of constraints: power balance, solar output & battery capacity	[99]
Solar–hydrogen power plants	Microcontroller utilization & Labview data	Balancing mechanism: energy output & consumption in real-time	Proper energy source for specific load	[100]

For wind energy-based hybrid power application, the overview of hybrid systems-based wind turbine, electrolyzer and fuel cell is simulated to show the dynamic response of hybrid system for high load demand and fast load changes. The dynamic modelling and control are designed based the multi-loop nonlinear predictive control framework for the safe operation and long-life performance [95]. Enhanced control strategy for the grid connected hybrid solar and wind energy under uncertainty parameters might be also obtained by rotor power management scheme from DFIG stator connected grid [96]. In addition, the modelling and controller design called robust tracking controller is important for the hybrid wind and battery systems [97]. The proposed controller is more effective during disturbance condition due to the wind and load fluctuation.

Finally, the review of hybrid power generation beyond the system thinking and cybernetic point of views, the hybrid system can be seen as dynamically complex adaptive systems in rural application. Therefore, the homeostatic regulation and control is very important to maintain the balance between coordinated power supply and demand response management [98]. This approach to the hybrid systems is focused on the technical operation aspect rather than socio-economic, environmental or regulatory aspects. In addition, the solution of optimal demand side management is proposed in hybrid power systems with optimal control method to schedule the power flow under minimum generation cost in one day and model predictive control to dispatch real-time power flow under disturbance condition [99]. An example, the management system for the hybrid control residential solar and hydrogen power system is presented. The controller is developed based on the microcontroller utilization supported by the Labview data acquisition systems [100]. The proposed controller may perform the balancing mechanism between the energy output and consumption in real-time.

4. Future Trends: Thermal Hybrid Power Generation

The efforts to maximize the benefits utilization of solar energy based solar thermal power systems with other types of generation system will be the future trends of hybrid power generation attempts. The optimal design parameters of hybrid systems based solar thermal and other thermal based power generation is investigated for the optimal cost and effective location within the objective function of minimum energy production cost [101]. The improved performance by means the thermodynamic analysis of solar tower power production during night time is proposed by the hybrid combination with waste to energy systems [102]. New strategy by the hybrid combination of power systems to solve the problems of environmental pollution and oil price increase and fluctuation. The study has reviewed the integrating of different schemes of solar thermal technology and geothermal gas plants [103]. Also, the thermodynamic perspectives are carried out to determine the limit performance of hybrid power generation-based PV cells and methanol thermal decomposition. The results of the study are important to design principle of highly efficient PV thermal and overall understanding of solar energy application [104].

The hybrid power based solar concentrating energy and biomass systems is numerically simulated from the thermodynamic performance and energy efficiency [105]. The promising research outcome is obtained for the efficient utilization of sunlight potentials, biomass resource and carbon gas reduction. The potentials of different solar technologies based solar thermal power plants hybrid with other type of generation systems. The hybrid of different solar thermal power technologies and biomass is investigated in terms of technology, climate data variation and economic feasibility [106]. In this case, the increasing temperature of steam from solar thermal systems is performed in biomass boiler in order to improve the thermodynamic performance and exergy capture in steam generation process [107]. Such kind approach may lead to the efficient utilization of renewable energy resources and to decrease the greenhouse gas emission. Meanwhile, hybrid of solar thermal based heliostat field collector with the most thermal input requirement is the new approach and viable solution to increase the share energy portion of renewable energy in the electricity grid in the future [108].

Theoretical model of hybrid types with low concentrated PV module and thermoelectric generator is presented to obtain the possible optimal design and system enhancement [109]. Non-equilibrium thermodynamic theory and law of energy conservation are applied for the performance characteristics in terms of efficiency and output power. The basis of performance optimization and analysis hybrid power generation parameters, such as Thomson effect in conjunction with Seebeck, Joule and Fourier heat conduction effects including the temperature difference of thermoelectric generator is simulated with Matlab environment [110]. In other cases, the thermodynamic method is used to investigate the hybrid performance of optimal design of PV-thermoelectric generator in terms of load mismatching, efficiency and output power [111]. The feasibility and performance of hybrid power generation in the form of thermal energy is reviewed in terms of optimal

operation, challenge and efficient enhancement for the future beneficial applications [112].

The review of hybrid system-based variety of solar energy systems with combine heat and power is presented. The study mentions that electrical modelling and analysis are limited, while limited study of economic and exergy system for the solar concentrating energy systems. Beside the technical overview of such hybrid systems, the economic issues are recommended for the further system development [113]. The hybrid combination of solar energy and combined cycle power generation is investigated with thermodynamic hybrid routine and thermal integration-based Brayton cycle [114]. In addition, the multiple sources with thermal hybrid power systems-based Brayton cycle is investigated from the thermodynamic performance including the energy and exergy analysis and the conversion efficiency with sensitivity analysis [115].

The model of hybrid power generation-based wind, electrolyser and fuel cell is presented taking the analysis of energy and exergy analysis based on thermodynamic, electro-chemical and mechanical models [116]. Similarly, the thermodynamic energy and sensitivity analysis are taken to investigate the hybrid performance based catalytic gasification, fuel cell, oxygen transfer membrane and gas turbine considering the overall thermal parameters of systems [117]. An example in hybrid type of solid oxide fuel cell and an internal combustion engine with the target of improving its efficiency and cost effectiveness using the methods of exergetic and exergoeconomic analysis [118]. The exergetic analysis identifies the location, magnitude, and sources of thermodynamic inefficiencies (exergy destructions and exergy losses) in the system; the largest exergy destruction takes place within the internal combustion engine, followed by the heat exchangers, and the solid oxide fuel cell (SOFC) stack. Meanwhile, exergoeconomic analysis: the cost structure of the SOFC-Engine hybrid system and the exergoeconomic factor of each component is quantified.

In comparison, the comprehensive review of hybrid system based solid oxide fuel cell and gas turbine is investigated in terms of numerical simulations, experimental analyses, and thermo-economic optimizations. The detailed analysis includes the control strategy for the load following characteristics, best performance of nominal capacity and efficiency reduction during the load fluctuation [119]. Meanwhile, the thermo-economic modelling of different configuration of hybrid systems based solid oxide fuel cell and gas turbine is presented to determine the high efficiency system performance, cost-effective operation and economic revenue of model [120]. The performance evaluation of hybrid system based solid oxide fuel cell and micro gas turbine is presented consider the comprehensive energy balance and power generation efficiency [121].

5. Final Remarks

Regarding the future development of hybrid power generation, the performance of different types of hybrid power generation based thermal configuration is proposed based on thermodynamic analysis [122]. The performance hybrid geothermal and fossil fuel based thermal generation systems is investigated in terms of thermodynamic performance [123]. Similarly, the thermodynamic assessment-based Rankine cycle is proposed for the hybrid systems based solar energy with thermal collector and thermal liquefied natural gas-based power generation. The system optimization includes equivalent efficiency and some existing indices like thermal, cold energy, and exergetic efficiency [124]. Also, the combination between gasified biomass and solar energy based concentrated solar thermal has been investigated in terms of thermodynamic Rankine cycle performance [125]. The increase in concentrated solar thermal process may have positive impacts on hybrid system efficiency and the availability of heat exchanger system will increase the synergy both energy systems. Similarly, the efficiency performance systems are evaluated in hybrid power based gasified biomass and concentrated solar thermal systems [126]. However, there will be complement behaviour of hybrid systems based solar energy and biomass is investigated in terms of thermodynamic performance with Rankine cycle and economic model that covers energy, exergy, economic and environmental perspectives [127]. Based on these facts, there have been ambitious plans to maximize the potential solar energy with other back-up energy sources to supply the electricity energy demand worldwide.

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