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Overview of Different Approaches Used in Optimal Operation Control of Hybrid Renewable Energy Systems

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Abstract**—**A hybrid energy system is a combination of renewable energy sources with back up, as well as a storage system used to respond to given load energy requirements. Given that the electrical output of each renewable source is fluctuating with changes in weather conditions, and since the load demand also varies with time; one of the main attributes of hybrid systems is to be able to respond to the load demand at any time by optimally controlling each energy source, storage and back-up system. The induced optimization problem is to compute the optimal operation control of the system with the aim of minimizing operation costs while efficiently and reliably responding to the load energy requirement. Current optimization research and development on hybrid systems are mainly focusing on the sizing aspect. Thus, the aim of this paper is to report on the state-of-the-art of optimal operation control of hybrid renewable energy systems. This paper also discusses different challenges encountered, as well as future developments that can help in improving the optimal operation control of hybrid renewable energy systems.

Keywords**—**Renewable energies, hybrid systems, optimization, operation control.

I. Introduction

CURRENTLY, many developed and developing countries use conventional fossil fuels, which are costly and produce a considerable amount of greenhouse gases, as the main sources of energy [1]. A need exists for more sustainable energy sources which can be cheaper, more reliable and have much less or zero negative impacts on the environment. For sustainable energy production, renewable energies (i.e. solar, wind, hydro, and biomass) are the most usable supply options [2].

Aside from all being renewable and sustainable, each of the energy sources has distinct characteristics and advantages that make it well suited for specific applications [3]. On the other hand, the main disadvantages of these types of energies are the unpredictable nature of their resources, as well as their strong reliance on weather and climatic conditions [4]. Therefore, they cannot always match the fluctuating load energy requirements each and every time. This issue can be successfully addressed by using the renewable sources integrated in a hybrid energy system with back-up, such as diesel generator and storage systems, such as fuel-cell or batteries; improving the cost effectiveness and availability of power supplied to the load [5]. The most important feature of such hybrid systems is to generate energy at any time by optimally using each source and storing the excess energy for the later use as demanded [6].

The proper selection of the hybrid system's components and their sizes, the optimal resource allocation, as well as the optimal operation control, are all critical steps in achieving cost effectiveness of the system [7], [8]. The problem linked to the interaction between various energy sources and the loads is non-linear due to the non-linearity of the resources; to the non-linearity of the load [9]. The optimal operation control of the system should ensure high system efficiency and reliability with very low cost. The main purpose of the optimal operation control should be to adequately respond to the load energy requirements at all times. Several works on optimal sizing have already been reported in literature but less focused on optimal operation control of hybrid renewable energy systems. The aim of this paper is to review on modern, advanced optimal operation control of hybrid renewable energy systems. It is expected that this work may be valuable for researchers to comprehend the recent trends regarding optimal operation control of hybrid renewable energy systems.

This paper is organized as follows: Section II presents the different pertinent review papers related to hybrid systems optimal operation control. Section III presents the available software packages and optimization-based operation control algorithms as they are used in the current literature. Section IV reviews papers dealing with reliability indexes linked to hybrid systems optimal operation control. Section V presents different works where the authors have attempted to develop mathematical models for hybrid systems optimal operation control. Section VI discusses different definite challenges encountered, as well as a research vision that can help in improving the optimal operation control of hybrid renewable energy systems. Finally, conclusions are given in Section VII.

II. Related Reviews on Optimal Operation Control

Few reviews regarding the optimal operation control of hybrid renewable energy systems have been conducted. Some of the relevant review publications related to the topic of this paper are summarized in the following.

Nema et al. [10] reviewed the state of the design, operation and control requirement of the stand-alone photovoltaic (PV) PV solar–wind hybrid energy systems using a conventional backup source, such as a diesel generator. The application of an advanced control technique like artificial intelligence for

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the energy management and optimal operation of hybrid energy was proposed for future work.

Nehrir et al. [11] summarized the available approaches for different renewable energy systems configuration, sizing and control, as well as energy management. The authors also discussed the current status and future tendencies of renewable energy power generation, the challenges facing the extensive deployment, and research vision for the future of renewable energy systems.

Banos et al [12], as well as Bernal-Agustın and Dufo-Lopez [13], have provided an overview of research developments relating to the use of optimization algorithms for renewable energies design, planning and control problems. The first conclusion of these studies is that there is an increase in number of papers that use traditional, as well as heuristic optimization methods to solve renewable energy problems. The authors have pointed out that Pareto-based multi-objective optimization and parallel processing are promising research areas in the field of renewable and sustainable energy.

Erdinc and Uzunoglu [14] examined different optimization methods including software tools as potential optimization techniques. The papers reviewed in this article were mostly based on sizing, not on optimal operation control.

Deshmukh and Deshmukh [15] reviewed the state of solar and wind hybrid renewable energy systems modeling. Descriptions of the methodologies commonly used for modeling system components are described. This is followed by a review of the work reported by several authors. It has been shown that from the 69 publications reviewed on hybrid solar and wind, only four are dealing with control in general, and none of them with optimal operation control.

Bajpai and Dash [16] presented a comprehensive review of the research in the four main areas, i.e. unit sizing, optimization, energy flow management and the modeling of hybrid renewable energy system components in the past 10 years. It has been noticed that this paper only summarizes the key parameters that influence or help in deciding the optimal energy management strategy. It does not give extensive information on optimal operation control.

Zhou et al. [17] reviewed the state of the simulation, optimization and control technologies for the stand-alone hybrid solar–wind energy systems with battery storage. They have found that continued research and development efforts in this area are still needed for improving the system's performance, establishing techniques for accurately predicting their output and reliably integrating them with other renewable or conventional power generation sources.

III. Software and Control Optimization Algorithms

Several optimization tools have been developed and extensively used in optimization applications. A comprehensive literature survey of available software tools used for hybrid renewable systems performance evaluation is available in [18]. The simulation results obtained using these tools often incorporate financial costing of the proposed hybrid system configuration [19], [20]. However, only the most relevant software tools as well as algorithms used in literature dealing with optimal operation control will be presented in this section.

Dufo-Lo´pez et al. [21] have developed the HOGA program (Hybrid Optimization by Genetic Algorithms). This program uses a Genetic Algorithm (GA) to design a PV-Diesel system (sizing and operation control of a PV-Diesel system). The program has been developed in C++. Two algorithms are used in HOGA. The main algorithm obtains the optimal configuration of the hybrid system, minimizing its Total Net Present Cost. For each vector of the main algorithm, the optimal strategy is obtained (minimizing the non-initial costs, including operation and maintenance costs) by means of the secondary algorithm. In the paper, a PV-Diesel system optimized by HOGA is compared with a stand-alone PV system that has been dimensioned using a classical design method based on the available energy under worst-case conditions. HOGA is also compared with a commercial program for optimization of hybrid systems such as Hybrid Optimization Model for Energy Renewable (HOMER) and HYBRID2. In [22], the same authors presented a study of the influence of mathematical models in the optimal design of PV-Diesel systems. For this purpose, HOGA has been used. The mathematical models of some hybrid system elements have been improved in comparison to those usually employed in hybrid systems design programs. Furthermore, a more complete general control strategy has been developed; the one that also takes into account more characteristics than those usually considered in this kind of design.

Razak et al. [23] discussed the optimization of the renewable energy hybrid system based on the sizing and operational strategy of the generation system using HOMER software. The sensitivity analysis was also performed to obtain the optimal configuration of hybrid renewable energy based on different combinations of the generation system.

Ahmed et al. [24] discussed an optimization solution of a hybrid system of renewable energy sources by using the HOMER software. They showed the importance of the emergency generator in order to ensure the reliability and the economy of the system. Fulzele and Dutt [25] developed a methodology for optimum planning of a hybrid PV-Wind system with some battery backup. The local solar radiation, wind data and components database from different manufacturers have been analyzed and simulated in HOMER to assess the technical and economic viability of the integrated system. The performance of each component has been evaluated and finally, sensitivity analysis has been performed to optimize the system at different conditions. In [26], Razak et al. discussed the optimization of the hybrid system in the context of minimizing the excess energy and cost of energy. The hybrid of pico hydro, solar, wind and generator and battery as back-up is the basis of the assessment. The system configuration of the hybrid is derived based on a theoretical domestic load at a remote location and local solar radiation, wind and water flow rate data. Three demand loads are used in the simulation using HOMER to find the optimum combination and sizing of components. In [27], the same authors reviewed an optimization of a renewable hybrid system in which pico hydro is considered a dominant component. The system focuses on maximizing the use of the renewable energy system while minimizing the use of a diesel generator. Initial evaluation is done using HOMER. Optimization viability is based on the component sizing and the hybrid operational strategy. Final evaluation by genetics algorithm is used to evaluate both conditions in minimizing the life cycle cost for optimum configuration. Performance of each component of the hybrid was evaluated. Sensitivity analysis is also performed to optimize the system at different conditions.

Nafeh [28] developed and applied an operational control technique, based on the use of the fuzzy logic controller (FLC) and the commonly used ON-OFF controller for a Photovoltaic-Diesel-Battery hybrid energy system. This control technique aims to reliably satisfy the system's load, and at the same time to optimize the battery and diesel operation at all working atmospheric conditions. The proposed hybrid energy system is modeled and simulated using MATLAB-Simulink and the Fuzzy Logic Toolbox. The FLC is mainly designed to overcome the nonlinearity and the associated parameters variation of the components included in the hybrid energy system; therefore, yielding a better system response in both transient and steady state conditions.

In [29], Luiz et al. presented the specification, design and development of a standalone micro-grid supplied by a hybrid wind-solar generating source. The goal of the project was to provide a reliable, continuous, sustainable and good-quality electricity service to users, as provided in bigger cities.

Woon et al. [30] reviewed an optimal control approach used by Tiryono et al. [31] to evaluate the differences in operating strategies and configurations during the design of a PV-diesel-battery model. However, [31] did not capture all realistic aspects of the hybrid power system. In this paper, optimal control models were analyzed and compared with three different simulation and optimization programs. The authors proposed several improvements to the current model to make it more representative to real systems.

Gupta [32] presented the flowcharts of the optimum control algorithm based on combined dispatch strategies, to achieve the optimal cost of battery incorporated hybrid energy system for electricity generation, during a period of time by solving the mathematical model, which was developed in one of their previous paper. The main purpose of the control system proposed here was to reduce, as much as possible, the participation of the diesel generator in the electricity generation process, taking the maximum advantage of the renewable sources available. The overall load dispatch scenario was controlled by the availability of renewable power, total system load demand, diesel generator operational constraints and the proper management of the battery bank.

Schmitt [33] developed SimPhoSys (Simulation of Photovoltaic Energy Systems) to simulate the performance of photovoltaic energy systems. Detailed mathematical models of the system components have been implemented in the MATLAB/Simulink environment. SimPhoSys provides component models only for the PV generator, battery, battery charge controller, electronic converter, diesel generator and various types of loads.

Engin [34] developed a procedure for sizing hybrid systems using mathematical models for the photovoltaic cell, wind turbine, and battery that are present in the literature. This sizing procedure can simulate the performance of different renewable sources combinations fulfilling the lowest energy cost. The output of the program displays the annual performance of the system, the total cost of the system, and the best size for the hybrid system.

IV. Operation Control and Hybrid System Reliability

Several performance indicators to evaluate the reliability of hybrid renewable systems have been reported in the literature [35]-[37]. Hence, this section will present only the research works where the most common reliability indices are used together with operation control strategies.

Diaf et al. [38] presented a methodology to perform the optimal sizing of an autonomous hybrid PV/wind system. The methodology aims at finding the configuration, among a set of systems components, which meets the desired system reliability requirements, with the lowest value of levelised cost of energy. Modeling a hybrid PV/wind system is considered as the first step in the optimal sizing procedure. The authors proposed more accurate mathematical models for characterizing the PV module, wind generator and battery. The second step consists of the optimized sizing of a system according to the loss of power supply probability (LPSP) and the levelised cost of energy (LCE) concepts.

Satar et al. [39] presented a hybrid system control algorithm, as well as a dispatched strategy design, in which wind is the primary energy resource with PV cells. The main task of the proposed algorithm is to take full advantage of the wind energy and solar energy when it is available and to minimize diesel fuel consumption. In this paper, the system operation cost was as a linear function of the total capacity in MW. No other mathematical model of the system's control was presented.

Ashari and Nayar [40] presented dispatch strategies for the operation of a solar PV–diesel– battery hybrid power system using 'set points'. This includes the determination of the optimum set points values for the starting and stopping of the diesel generator in order to minimize the overall system costs. A computer program for a typical dispatch strategy has been developed to predict the long-term energy performance and the lifecycle cost of the system.

Rashtchi et al. [41] introduced hybrid PV-Fuel Cell generation system for a typical domestic load that is not located near the electric grid. In this configuration, the combination of a battery, an electrolyzer, and a hydrogen storage tank were used as the energy storage system. The aim of this design was minimization of the overall cost of generation scheme over 20 years of operation. Energy-based modeling has been developed using MATLAB/Simulink to observe evolution of the system during a typical day, and the results are reported and discussed. An overall power management strategy was designed for the proposed system to manage power flows among the different energy sources and the storage units in the system.

Dursun and Kilic [42] presented different power management strategies of a stand-alone hybrid power system. The system consists of three power generation systems, PV panels, a wind turbine and a proton exchange membrane fuel cell (PEMFC). The PV and wind turbine are the main supply for the system, and the fuel cell is used as a backup power source. Therefore, an energy storing device is needed to ensure continuous energy supply. In this proposed hybrid system, gel batteries were used. The state of charge (SOC), charge-discharge currents are affecting the battery energy efficiency. In this study, the battery energy efficiency is evaluated with three different power management strategies. The control algorithm was made possible through the use of MATLAB-Simulink.

In [43], a stand-alone hybrid power generation system including different power sources such as wind turbine generators, photovoltaics, and storage batteries is designed by minimizing total costs and maximizing reliability simultaneously using Particle Swarm Optimization (PSO). The system operation strategies are presented in terms of power balance. In [44], the same authors have designed a grid-connected hybrid generating system comprising of wind turbine generators, photovoltaic panels, and storage batteries. In this system design, three design objectives were considered, that is, costs, reliability, and pollutant emissions. Considering the complexity of this problem, the authors have developed a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm to derive a set of non-dominated solutions, each of which represents a candidate system design. A numerical example is discussed to illustrate the design procedure and the simulation results are analyzed.

Ardakani [45] designed a hybrid wind-PV-battery generation system. The aim of this design is minimize the annualized cost of the stand-alone system over 20 years of operation. The optimization problem was subject to economic and technical constraints. System costs entailed the initial investment, replacements, operation and maintenance, as well as loss of load costs. The technical constraint, related to system reliability, was expressed by the equivalent loss factor. The reliability index was calculated from component's failure, that includes wind turbine, PV array, battery and inverter failure. In [46] the same authors conducted a similar study with a grid-connected hybrid wind-PV-battery power system.

Razak et al. [47] reviewed the application of genetic algorithms in optimization of hybrid system consisting of a pico hydro system, solar PV modules, diesel generator and battery sets. The system focused on maximizing the use of the renewable system while minimizing the use of a diesel generator. The hybrid system configuration was derived based on the required load. Optimization viability was based on the component sizing and the hybrid operational strategy. Frugal option, state of charge of the batteries and power supplied by each component of the hybrid were the main criteria in deciding the best operational strategy.

Muralikrishna and Lakshminarayana [48] analyzed the system size and performance against the influence of the Deficiency of Power Supply Probability (DPSP), Relative Excess Power Generated (REPG), Energy to Load Ratio (ELR), fraction of PV and wind energy, and coverage of PV and wind energy. The methodology of Life Cycle Cost (LCC) for economic evaluation of a stand-alone PV system, stand-alone wind system and PV-wind hybrid system was developed and simulated using the model.

In [49], time-series models were used to determine optimal dispatch strategies, in conjunction with optimally-sized components, in remote hybrid power systems. The objective of the dispatch optimization was to minimize the costs associated with diesel fuel, diesel starts, and battery erosion, based on a thorough economic analysis of present worth life-cycle cost. An ideal predictive control strategy was used as a basis of comparison. The authors used a simplified time-series model to obtain preliminary conceptual results. These results illustrate the nature of the optimal dispatch strategy and indicate that a simple State of Charge (SOC) set-point strategy can be practically as effective as the ideal predictive control.

Kaviani el al. [50] designed a hybrid wind-PV-fuel cell generation system to supply power demand. The aim of this design was minimization of annualized cost of the hybrid system over its 20 years of operation. The optimization problem was subject to reliable supply of the demand. Three major components of the system, i.e. wind turbine generators, photovoltaic arrays, and AD/DC converter, may be subject to failure. Also, solar radiation, wind speed, and load data were assumed entirely deterministic. System costs included the initial investment, replacements, and operation and maintenance, as well as loss of load costs.

Yang et al. [51] recommended an optimal sizing method to optimize the configurations of a hybrid solar-wind system employing battery banks. Based on a GA, which has the ability to attain the global optimum with relative computational simplicity, one optimal sizing method was developed to calculate the optimum system configuration that can achieve the customers required loss of power supply probability (LPSP) with a minimum annualized cost of system (ACS). The decision variables included in the optimization process were the PV module number, wind turbine number, battery number, and PV module slope angle and wind turbine installation height.

Sánchez et al. [52] presented the optimal sizing of a generation system wind-PV-fuel cell, such that demand of an isolated residential load is met. The function objective was constituted by the costs of the system, and the solution method employed was based on PSO. The aim of this work was to minimize the total cost of the system such that demand is met. In order to compare the performance of PSO with other methods, the sizing of the renewable generation system was made also by the heuristic method called Differential Evolution.

Dehghan et al. [53] presented a hybrid wind-PV plant with the aim of supplying the Institute of Electrical and Electronics Engineers (IEEE) reliability test system load patterns. The plant capital investment costs were minimized by applying a hybrid particle swarm optimization (PSO)/harmony search (HS) approach, and the system fulfills the appropriate level of reliability.

Hassanzadehfard et al. [54] formulated the optimization problem as a nonlinear integer minimization problem which minimizes the sum of the total capital, operational and maintenance and replacement cost of Distributed Energy Resources (DERs), subject to constraints such as energy limits of each DER. The authors proposed Particle Swarm Optimization (PSO) for solving this minimization problem. In this paper some notions of reliability were considered for micro-grid, and the effect of reliability on total cost of micro-grid was evaluated.

Kirthiga and Daniel [55] used PSO and modified GA optimization techniques to find the sizes of hybrid renewable system for autonomous operation. The authors have developed a MATLAB code for a standard 33 bus distribution system used to demonstrate the effectiveness of the methodology.

Bashir and Sadeh [56] proposed a new algorithm for determining the capacity of hybrid wind-PV-battery generation system considering the uncertainty in wind and PV power production. The algorithm used to determine the capacity of wind, PV and battery for supplying a certain load was formulated as an optimization problem that the objective function was the minimization of the cost and with the constraint of having specific reliability. In [57], the same authors have considered the combination of wind-PV-tidal as the primary, and a battery as an auxiliary source, for which determining the capacity was formulated as an optimization problem. The objective function was the minimization of the cost with the constrain having Equivalent Loss Factor (ELF) as specific reliability index. Particle Swarm Optimization (PSO) was used for optimal sizing of the system. Simulation results were carried out by MATLAB software. It is shown that the hybrid system is the best configuration that has minimum cost and can satisfy all constrains.

Hakimi et al. [58] applied a novel intelligent method to the problem of sizing in a hybrid power system such that the demand of residential area was met. The system consisted of fuel cells, some wind units, some electrolyzers, a reformer, an anaerobic reactor, and some hydrogen tanks. The system was assumed to be stand-alone and uses biomass as the available energy resource. System costs entailed the initial investment, replacements, and operation and maintenance, as well as loss of load costs. A particle swarm optimization algorithm is used for optimal sizing of the system's components.

Jalilzadeh, Kord and Rohani [59] introduced a method to unit sizing a hybrid PV-fuel cell generation system for a typically isolated domestic load with the aim of finding the configuration, among a set of systems components, which meets the desired system reliability requirements, with the lowest value of levelized cost of energy over 20 years of operation. The authors designed a strategy for the proposed system to manage power flows among different energy sources and storage units.

Hu and Solana [60] presented a general model based on real option theory for evaluating a hybrid diesel-wind generation plant. A dynamic programming method has been used to generate the optimum operational option by maximizing the net cash flow of the plant. Results showed that operational options can provide additional value to the hybrid power system when this operational flexibility is correctly utilized. This paper also provided a framework to find the optimal operating decision at each time step based on the real option model.

Giannakoudis et al. [61] addressed the design and optimization problem under uncertainty of power generation systems using renewable energy sources and hydrogen storage. A systematic design approach was proposed that enables the simultaneous consideration of synergies developed among numerous sub-systems within an integrated power generation system and the uncertainty involved in the system operation. The Stochastic Annealing optimization algorithm was utilized to handle the increased combinatorial complexity and to enable the consideration of different types of uncertainty in the performed optimization. A parallel adaptation of this algorithm was proposed to address the associated computational requirements through execution in a Grid computing environment. Numerous design and operating parameters were considered as decision variables, while uncertain parameters were associated with weather fluctuations and operating efficiency of the employed sub-systems. The obtained results indicated robust performance under realizable system designs, in response to external or internal operating variations.

V. Optimal Operation Control Modeling

Several mathematical models have been developed with different objectives, such as optimizing the hybrid system operation costs, pollutant emissions, unmet load, fuel consumption, etc. Therefore, this section will present the major works done by authors who attempted to develop mathematical models for hybrid system optimal operation control.

Bernal-Agustın and Dufo-Lopez [62] presented a triple multi-objective design of isolated hybrid systems minimizing, simultaneously, the total cost throughout the useful life of the installation, pollutant emissions (CO_2) and unmet load. For this task, a multi-objective evolutionary algorithm (MOEA) and a GA have been used to find the best combination of components of the hybrid system and control strategies. In [63]-[65], Bernal-Agustın et al. applied the strength Pareto evolutionary algorithm to the multi-objective design of renewable hybrid systems, with the aim of minimizing the life cycling cost and the unmet load together. For the system optimal sizing and operation control, an MOEA and GA have been used. A novel control strategy has been developed and explained in this article.

Seeling-Hochmuth [66] developed a method to jointly determine and optimally incorporate the sizing and operation control of hybrid-PV systems. This model is based on the current flow through the system from the generators to the loads. The different operation strategies, from which depends the current flow, as well as the operation costs, can be chosen by making a search through the possible system's operation control settings. The algorithm used is divided into a main (sizing) and a sub-algorithm (operation optimization), respectively.

Dagdougui et al. [67], presented a model for integrated hybrid system based on a mix of renewable energy technologies comprising an electrolyzer, hydroelectric plant, pumping stations, wind turbines and fuel cell. The model is developed with the aim of optimizing the control of energy storage while satisfying the hourly variable electric, hydrogen, and water demands or real time operational management.

Gupta et al. [68] analyzed and designed a mixed integer time series linear programming model for optimal cost and operation of a hybrid energy generation system consisting of a PV array, biomass, biogas, micro hydro, a battery bank and a fossil fuel generator; based on demand and potential constraints.

Dagdougui et al. [69] have presented the structural Decision Support System (DSS) that can be used for the optimal energy management at a local scale through the integration of different renewable energy sources. The integrated model of a grid connected hybrid energy system components is developed. The system is composed of PV and solar thermal modules, wind and biomass plant. Furthermore, a framework is presented to optimize the different means of ensuring the micro-grid's electrical and thermal energy demand, as well as the water demand, with specific reference to the presence or absence of a storage system. To finish, the optimization model has been applied to a case study.

Sopian et al. [70] reviewed the application of genetic algorithms in optimization of hybrid systems based on the component sizing and the operational strategy. Genetic algorithms are used to find the best configuration based on the lower net present cost. Random selections of sizing and operation strategy, as well as sensitivity analysis are also performed to optimize the system under different conditions.

Ashok [71] discussed different hybrid system's components and developed a general mathematical model to find an optimal selection of energy components minimizing the life cycle cost. The optimal dispatch strategy of hybrid energy system consists in finding the most economical schedule for different combinations of the system components, satisfying load requirements, resource availability and equipment constraints.

Tazvinga et al. [72] developed a hybrid system model incorporating PV and diesel generator in which the daily energy demand fluctuations for different seasonal periods of the year in order to evaluate the equivalent fuel cost, as well as the operational efficiency of the system for a 24-h period. The results show that the developed model can give a more realistic estimate of the fuel costs reflecting fluctuations of power consumption behavior patterns for any given hybrid system.

VI. Limitations and Future Works in Hybrid Renewable Systems Optimal Operation Control

It is known that the search space in HOMER is the set of all allowable sizes and number of modules of each component. Hence, HOMER evaluates each system's configurations defined by the user in the search space by raking them based on the Net Present Cost (NPC) taken as a performance index. The more values the user will define for a particular decision variable (size or number), the longer HOMER will run and the higher the chance of getting better solution (sub-optimal solution). It turns out that the specification of the search space by the user involves a tradeoff between accuracy (better sub-optimal solution) and computational time (run time). Hence, an approach based on a mathematical optimization model taking the system detailed running (operation) costs as objective function to be minimized, as well as different operation constraints is of great interest.

From the studied literature, it has been noticed that most of the previously published research works have assumed a fixed load and uniform daily operational cost which can be extrapolated to get the monthly or yearly cost. It has also been noticed that complete and detailed mathematical formulations are not given in most papers dealing with optimal operation control. The following shortfalls can be pointed out:

- The diesel generator lubricant and emission penalty costs are not taken into account when used in the architecture of the hybrid system.
- The salvage values of different hybrid system components are not taken into account.
- Realistic kinetic batteries dynamics model in terms of recharge and discharge rates.
- Reliability constraints are usually neglected in most research works dealing with sizing and operation control of hybrid systems.
- Some renewable energy sources are not included in most of developed hybrid system models (such as Waves, Tidal, Hydrokinetic, etc.).
- Also not all types of energy storage systems are included (such as flywheel, etc.).

Thus for future work, renewable sources such as Waves, Tidal, and Hydrokinetic should be included in the architecture of hybrid systems to assess their impact on the system operation control. It would also be of great interest to incorporate the future load demand prediction, as well as the renewable resources forecasts as part of the operation control of the hybrid power systems.

Further research and development should also be conducted to solve the conflict between optimal solutions that minimize the NPC of the hybrid system while meeting reliability requirements. Real-time optimal control algorithms of the hybrid systems, such as Model Predictive Control (MPC), also need to be studied because most current optimal control algorithms developed so far are not applicable in real-time; they are just used as a benchmark solution.

VII. CONCLUSION

This paper provides an overview of the research developments in the area of optimal operation control applied to hybrid renewable energy systems. Several papers from major referenced journals in the area of renewable hybrid system control have been reviewed. One of the conclusions of this work is that that there is a significant number of research papers dealing with optimal sizing of hybrid systems; however, only few research works have been dedicated to optimal operation control of hybrid renewable energy systems. Literature dealing with the current status of different optimal control approaches, their applications, as well as limitations in the area of hybrid renewable systems has been discussed. This paper has also highlighted and suggested future works that can make significant contribution to the hybrid systems optimal operation control research area.

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