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Control and Management of Hybrid Renewable Energy Systems: Review and Comparison of Methods

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Abstract- *Hybrid renewable energy systems (HRES) have been introduced to overcome intermittent nature of single-source renewable energy generation. In order to utilize HRES optimally, two issues must be considered: optimal sizing and optimal operation. The first issue has been considered vastly in several articles but the second one needs more attention and work. The performance of hybrid renewable energy systems highly depends on how efficient the control of energy production is. In this paper, paradigms and common methods available for control and management of energy in HRES are reviewed and compared with each other. At the end, a number of challenges and future research in relation to HRES are addressed.*

Keyword: Hybrid energy systems, Control paradigm, Energy management, Renewable energy.

1. INTRODUCTION

Electric energy is one of the important requirements of any country because it has a vital influence on their social and economic development [1-4]. Till now, a significant portion of energy demand has been heavily dependent on fossil fuels like natural gas, coal and etc. The mentioned conventional energy sources have a number of drawbacks such as the great volatility in costs, limited and inadequately distribution on the earth's crust, harmful emissions and etc. On the other hand, rapid increase in energy demand has led to a gap between production and demand of energy [5-9]. To solve the problems raised, renewable energy resources such as wind, photovoltaics (PV), micro hydro and etc, can be a suitable solution [10,11]. Due to intermittent nature of many renewable energy sources and their dependence on environmental conditions, hybrid combinations of two or more of renewable energy sources can improve system's performance [12,13]. Hybrid renewable energy systems (HRES) can work in stand-alone (SA) or grid connected (GC) mode. HRES have main advantages in comparison to single source system. Some of these benefits have been shown in Fig.1. In this paper, paradigms and common methods available for control and energy management of HRES are reviewed and compared with each other.

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2. Control and energy management

An optimal energy management strategy ensures a cost effective and reliable integrated energy system. Typically, a control system is required to determine and assign active and reactive output power dispatch from each energy source while keeping its output voltage and frequency at the desired limit. Most of the authors used storage state of charge, bus voltage and bus frequency as control parameters for energy flow management in HRES. To develop an intelligent energy flow management in HRES, renewable energy sources and load are forecasted at first stage and optimized at second stage. The control systems can be classified into three categories viz: centralized, distributed and hybrid control paradigms and in all of them, each energy source is assumed to have its local controller that can determine optimal operation of the corresponding unit based on current information [7,13-15].

A typical data communication and power flow in HRES is shown in Fig. 2.

2.1. Centralized control paradigm

In centralized control paradigm, the entire system comprised of one centralized controller and several local controllers for various renewable energy resources and energy storage systems. In this paradigm, the measurement signals of all energy resources in a group are sent to centralized controller as shown in Fig. 3. The centralized controller acts as an energy supervisor and makes decision on control actions on the basis of all measured signals and a set of predetermined objectives and constraints.

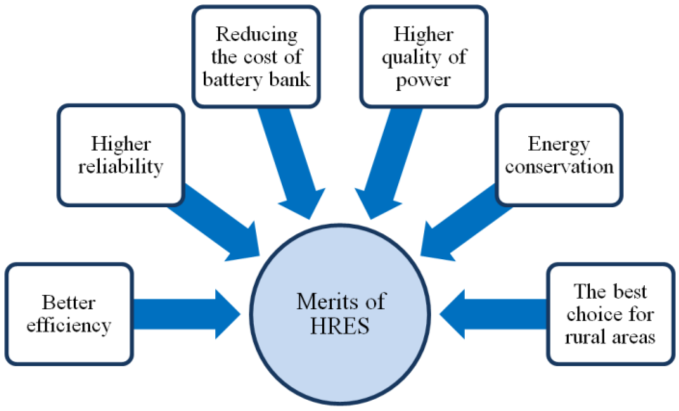

Fig. 1. Main advantages of HRES.

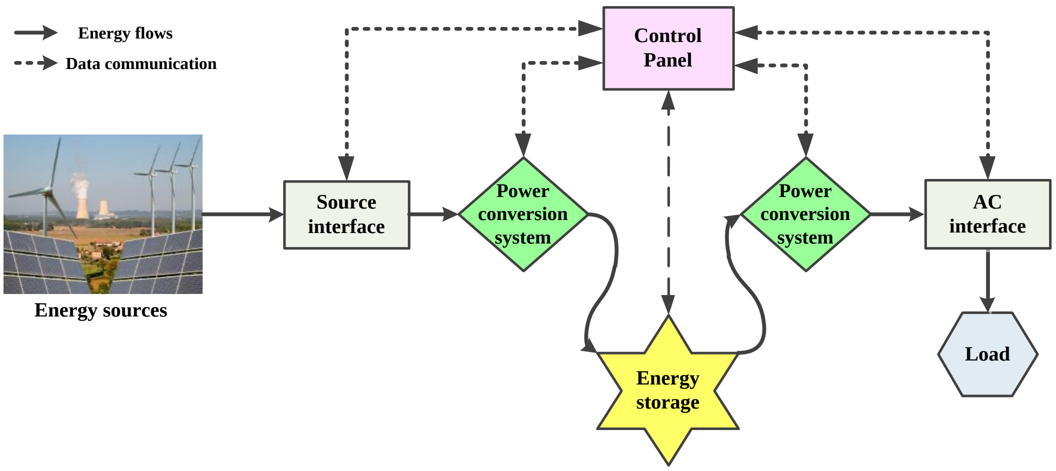

Fig. 2. Typical data communication and power flow in HRES.

Depending upon the availability of resource generation and load demand, it will prioritize and manage energy flow among various renewable energy resources in HRES [16-20].

2.2. Distributed control paradigm

In distributed control paradigm, each energy source sends measurement signals to its local controller as shown in Fig.4. The local controllers communicate with one another to take appropriate decision for global optimization [21,22].

2.3. Hybrid control paradigm

Hybrid control paradigm is combination of centralized and distributed control schemes. In such scheme, renewable energy sources are grouped within integrated system. Centralized control scheme is applied within each group and distributed control scheme is used to coordinate each group.

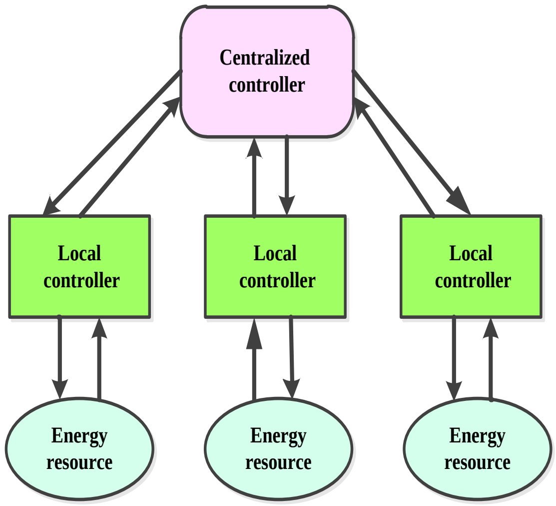

Fig. 3. Centralized control paradigm.

In such hybrid control paradigm, local optimization is achieved via centralized control within each group, while global coordination among the different groups is achieved through distributed control [23]. A hybrid control paradigm is shown in Fig. 5.

Many papers are reported in literature which deals with system control for energy flow management of HRES. In [24] a controller that evaluated the power available from each of the system components and environmental credit of the system is designed. In [25] load following control of fuel cell (FC) based on power flow balance is discussed. In [26] dispatch strategies and used optimum values of set points for the starting and stopping of the diesel generator to minimize the overall system cost is presented. In [27] the dynamic behavior of the integrated system under different values of wind speed, solar radiation and load demand is tested. In [28] fuzzy regression model (FRM) is used for maximum power point tracking of PV arrays to extract peak available power. H2 generated by electrolyzer was stored in a tank for lower insolation levels or at night FC operation. In [29] hierarchical control including a master-slave control strategy for HRES is developed. At particular instant, energy source was selected as per the generation cost by master control strategy. Slave control scheme maintained constant DC bus voltage under transient conditions by changing the duty cycle of DC/DC converters. In [30] additional power generated was used to charge the ultra-capacitor (UC) bank.

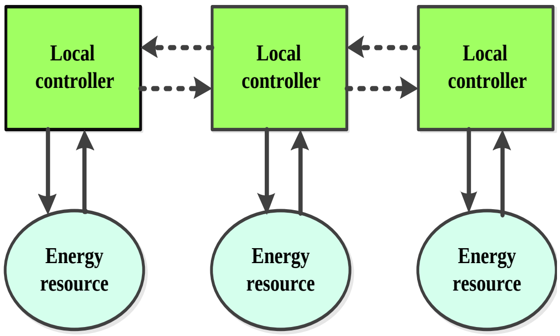

Fig. 4. Distributed control paradigm.

During peak demand, UC bank supplied the surplus power demand and also it compensated the tracking mismatches and delayed of the FC system that generally showed reasonably sluggish response time. In [31] stabilization problems in the integrated system using the intelligent fuzzy logic controller on the basis of flatness property for DC grid voltage regulation is discussed. In [32] an optimum configuration and dispatch strategies in solar-wind based hybrid system is presented. In [33] constant voltage at AC bus by controlling DC-link voltage with modulation index of PWM inverter is maintained. In [34] PI/PID controllers to regulate the output power from the sources and demand under varying condition of load and generation and this reduced the frequency deviation is used. In [35] authors, proposed a strategy that was compared with a conventional strategy. They minimized number of change over between FC and battery with the help of measurement and time delay elements. In [36], first fuel cell system supplied the deficit power to load and later UC bank satisfied the remaining energy for short duration that cannot be fulfilled by the FC system. In [37] transient analysis of a self-excited induction generator with electronic load controller for stand-alone applications is presented. Analysis includes the effect of switching of loads on dump power, load power and generated power. In [38] authors proposed three power management strategies (PMS) and compared them on the basis of sensitivity analysis, considering state of charge of batteries and output power from FC. They also observed the effect of these PMS on lifetime of FC and electrolyzer. In [39] based on the battery storage energy, authors proposed six operating points where the DG was either switched off or on. This control technique minimized the fuel consumption and storage capacity of the battery.

Various studies on system control of HRES are reported in literature and summarized in Table 1.

3. Comparison of control paradigms

The availability of power from a hybrid system can be economically maximized by choosing proper control technique in the system design process [49]. This section presents advantages and drawbacks of each of the above mentioned control paradigms to find appropriate control paradigms of HRES.

In centralized control paradigm, the multi-objective energy management system can achieve global optimization based on all available information, but this control paradigm suffers from heavy computation burden and is subject to single-point failures (a single point of failure is a part of a system that, if it fails, will stop the entire system from working). In distributed control paradigm, the computation burden of each local controller is greatly reduced without any single-point failure problems, but this control paradigm has complex communication system among local controllers.

A promising approach for distributed control problems is the multi agent system (MAS). MAS is discipline that focuses on collective behaviors produced by the interactions of several autonomous entities called agents, these interactions revolve around cooperation, competition or coexistence between these agents,

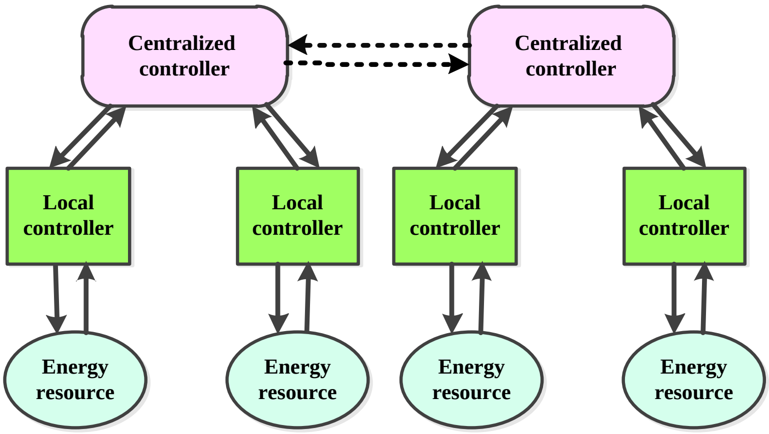

Fig. 5. Hybrid control paradigm.

Table 1. Summary on system control of HRES.

Reference	Energy sources considered	Outcome
[24]	Wind, PV, battery	Designed a controller that evaluated the power available from each of the system components and environmental credit of the system.
[25]	PV, wind, FC, battery, UC	Discussed load following control of fuel cell (FC) based on power flow balance. Batteries and UC are used as backup energy storage system to compensate the system dynamics.
[26]	PV, diesel generator (DG), battery	Presented dispatch strategies and used optimum values of set points for the starting and stopping of the diesel generator to minimize the overall system cost.
[27]	Wind, PV, FC, UC	Tested the dynamic behavior of the integrated system under different values of wind speed, solar radiation and load demand.
[28]	PV, FC	Fuzzy regression model (FRM) is used for maximum power point tracking of PV arrays to extract peak available power. H_2 generated by electrolyzer was stored in a tank for lower insolation levels or at night FC operation
[29]	PV, wind, FC, battery	Hierarchical control including a master-slave control strategy for HRES is developed. At particular instant, energy source was selected as per the generation cost by master control strategy. Slave control scheme maintained constant DC bus voltage under transient conditions by changing the duty cycle of DC/DC converters.
[30]	PV, FC, UC	Additional power generated was used to charge the UC bank. During peak demand, UC bank supplied the surplus power demand and also it compensated the tracking mismatches and delayed of the FC system that generally showed reasonably sluggish response time.
[31]	PV, FC, super capacitor (SC)	Discussed stabilization problems in the integrated system using the intelligent fuzzy logic controller on the basis of flatness property for DC grid voltage regulation.
[32]	PV, wind, battery	Presented an optimum configuration and dispatch strategies in solar-wind based hybrid system.
[33]	Wind, solar, battery, FC, battery, UC	Maintained constant voltage at AC bus by controlling DC-link voltage with modulation index of PWM inverter.
[34]	Solar thermal, DG, wind, FC, battery, flywheel, UC	Used PI/PID controllers to regulate the output power from the sources and demand under varying condition of load and generation and this reduced the frequency deviation.
[35]	PV, FC, battery	Proposed a strategy that was compared with a conventional strategy. Also minimized the number of change over between FC and battery with the help of measuring and time delay elements.
[36]	Wind, FC, UC	First fuel cell system supplied the deficit power to load and later UC bank satisfied the remaining energy for short duration that cannot be fulfilled by the FC system.
[37]	Micro hydro	Presented transient analysis of a self-excited induction generator with electronic load controller for stand-alone applications. Analysis includes the effect of switching of loads on dump power, load power and generated power.
[38]	PV, wind, FC, battery	Proposed three power management strategies (PMS) and compared them on the basis of sensitivity analysis, considering state of charge of batteries and output power from FC. Also observed the effect of these PMS on lifetime of FC and electrolyzer.
[39]	PV, diesel generator, battery	Based on the battery storage energy, authors proposed six operating points where the DG was either switched off or on. This control technique minimized the fuel consumption and storage capacity of the battery.

Table 1. Summary on system control of HRES (continued).

Reference	Energy sources considered	Outcome
[40]	PV, wind, FC	Four energy control strategies are proposed and analyzed for the standalone Renewable/Fuel Cell Hybrid Power Source (RES/FC HPS). The concept of the load following (LF) and Maximum Efficiency Point Tracking (MEPT) is used to control the fueling rates.
[41]	PV, FC, electrolyzer, battery bank, SC	Proposed an advanced energy management strategy for a stand-alone hybrid energy system. The control strategy is designed to ensure an optimal energy management of the hybrid system. This strategy aims to satisfy the load demands throughout the different operation conditions and to reduce the stress on the hybrid system.
[42]	PV, wind, battery	The control strategy based on a communication link increases the control complexity and affects the expandability of the HRES. The master-slave control with the droop concept does not require a communication link and provides good load sharing. In addition, the master–slave concept adds features, such as the flexibility, expandability and modularity of the HRES.
[43]	PV, battery, FC	The energy management strategy was based on diverting any excess PV energy into the electrolyzer when the battery is charged to 99.5%. This will protect the battery from overcharging. In this developed strategy, no need for a dump load as the generated energy is matched with the load demand.
[44]	PV, FC, UC	The purpose of the energy management strategy is to satisfy the load requirement continuously. The priority is to utilize the PV energy and any excess energy is used to generate hydrogen. The excess energy is directed to the ultra-capacitor when the hydrogen storage system is full. The solar system will be shut down if the capacitor is fully charged.
[45]	PV, battery, FC	The strategy was based on weather forecasts and the objective of the control strategy is to optimize the use of renewable sources to ensure their use while improving the comfort conditions of the house.
[46]	PV, wind, micro-hydro power, diesel, battery	A distributed energy management system architecture based on multi agents was proposed. The purpose is to provide control for each of the energy sources or loads in the micro-grid system.
[47]	PV, wind, battery, FC	Forecasting of both the renewable sources as well as loads was carried out prior to implement the proposed strategy. The power management system is continuously updated by updating both the decision time interval and any time lags resulted from hardware sensors.
[48]	PV, wind, diesel, battery	Three energy management strategies were checked: cycle charging strategy, peak shaving strategy, load following strategy. The cycle charging strategy was found to be the most effective in comparison with other strategies.

Table 2. Summary of merits and demerits of control paradigms for HRES.

Control paradigm	Merit	Demerit
Centralized control paradigm	Multi-objective energy management system can achieve global optimization based on all available information.	This paradigm suffers from heavy computation burden and is subject to single-point failures.
Distributed control paradigm	The computation burden of each controller is greatly reduced, and there are no single-point failure problems.	Potential complexity of its communication system.
Hybrid control paradigm	Computational burden of each controller is reduced, and single-point failure problems are mitigated.	Potential complexity of its communication system.

introducing the issue of collective intelligence and the emergence of structures interactions. MAS has been used, for example, for power system integration, restoration, reconfiguration, and power management of microgrids [13,50]. Artificial algorithm like fuzzy logic, artificial neural networks, genetic algorithm and their hybrid combination are the possible options for solving such problems of distributed control paradigm [51,52].

Hybrid control paradigm minimizes computational effort on centralized and local controller hence reduces single-point failure problems in HRES.

By examining the benefits and problems of each control arrangement, we can conclude, among all the control paradigms, combination of centralized and distributed control schemes, in the other words, hybrid control paradigms are quite suitable and reliable in HRES.

Summary of merits and demerits of control paradigms, are listed in Table 2.

4. Optimal energy flow management in HRES

An optimal energy flow management among various energy sources in HRES is necessary because the power output from renewable sources is intermittent and depends on several uncontrolled conditions. The dynamic interaction between various energy sources and loads often requires a careful study of transient response of such systems [53-56].

depends on several uncontrolled conditions. The dynamic interaction between various energy sources and

loads often requires a careful study of transient response of such systems [53-56].

The energy management strategy should ensure high system efficiency and high reliability with least cost. The main objective of the technique should be to supply the peak load demand at all times. In HRES, fuel cells can be used as long term energy storage option. However the slow dynamics of fuel cells and its degradation due to frequent start-up and shut down cycles is a major disadvantage. Hence batteries are used in such hybrid systems to take care of power deficits and to act as a short term energy storage medium. The combination of fuel cells and batteries along with PV ensures uninterrupted power supply to the load. key parameters that influence or help to decide optimal energy management strategy have been summarized as follows [6,57-61]:

- Useful electrical energy available from the primary renewable energy sources, such as solar PV and wind turbines.
- Capital cost, operating cost, lifetime and days of autonomy of storage devices, such as batteries, ultra-capacitors and fuel cells.
- State of charge of storage devices or the pressure level of hydrogen tanks in case of hydrogen energy systems.
- The number of start-up and shut down cycles for fuel cells and electrolyzers.
- Fuel price in case of hybrid systems involving diesel generator.

5. Challenges and future trends in HRES

Although power generation using renewable energy sources is sustainable and environment friendly, however several challenges are still exist. The following lists some of the important challenges and scope for future research:

- Need for development of smart mini-grids consisting of various different generators which will interact with each other and work intelligently to deliver power according to the requirement.
- As deployment of HRES in the form of independent microgrid increases, the need for real-time energy management of such systems, and robust communication between the individual energy sources of the microgrid become important task and therefore, deserve further attention.
- For stability issues of HRES, it is required to carry out transient analysis of system by step changes in the variable parameters like solar radiation, wind speed and load demand.
- Due to development of modern equipment and household appliances that use dc voltage, several researchers have explored the virtue of dc microgrid for localized loads and the idea of completely rewiring homes to run on dc. This venue deserves further attention to explore its technical and economic feasibility.

6. CONCLUSIONS

Hybrid renewable energy systems are suitable alternatives for single-source renewable energy systems due to intermittent nature of most of them. Proper control of HRES is critical to achieve highest system reliability and operation efficiency. In this paper, paradigms and common methods available for control and energy management of HRES are reviewed and compared with each other. Among all possible control paradigms, hybrid control paradigms are quite suitable and reliable in HRES. In this control paradigm, local optimization is achieved via centralized control within each group, while global coordination among the different groups is achieved through distributed control and this paradigm is recognized as the best option for robust control of HRES without single-point failure problems. Also, a number of challenges and future research in relation to the HRES are addressed.

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