Decentralized Hybrid Renewable Energy Systems

Control Optimization and Battery Ageing
Estimation Based on Fuzzy Logic

A Dissertation
in Candidacy for the Degree of
Doctor in Engineering (Dr. Eng.)

Elektrische Energieversorgungssysteme
Elektrotechnik/ Informatik
Universität Kassel

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Dissertation day: May 22, 2002

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Acknowledgements

I am most grateful and highly indebted to Prof. Werner Kleinkauf for his invaluable supervision, guidance and encouragement throughout the whole research work.

My gratitude is also due to Prof. Jürgen Schmid for his strong support and useful discussions throughout this thesis.

This thesis has been partially financed by a scholarship from the German Academic Exchange Service (DAAD). I would like to thank the DAAD organization for their support.

The main part of this research has been done at the Institute of Solar Energy Supply Technology (ISET), thus my thanks are due to the research staff and colleagues of ISET, especially the colleagues of the system technology department, for their useful help and fruitful discussions during the development phases of my research.

Special appreciation is due to my colleagues of the department of power supply systems IEE-EVS at Kassel University, who supported and helped me during different phases of my research.

Furthermore, my thanks aims at the colleagues of the National Research Center (NRC) in Egypt who provided me with the necessary data for the village of Borg Al-Arab.

Finally, a special word of thanks to my wife who helped me to make this work a reality.

Mohamed Ibrahim
Summary

Decentralized renewable hybrid systems represent a sustainable power supply option for remote and rural areas. However, up to date the control routines of the realized hybrid systems are not fully optimized and consequently cause low reliability and high costs. These are the main reasons restricting the dissemination of such systems. Therefore, optimizing system design (configuration, topology, sizing and control) will provide a significant potential to improve system performance criteria (fuel consumption, storage lifetime and costs). The constraints imposed on the operation of individual system components represent the fundamental potential of improving the overall technical and economic performance of hybrid supply. Accordingly, in this research work an advanced control concept which optimizes the operation of decentralized PV/wind/diesel/battery hybrid systems is developed.

Based on the fuzzy logic knowledge-based system, a process is developed that uses the measured current, voltage and temperature of the battery to estimate the basic lead-acid battery degradation mechanisms and their dynamic influence on its ageing. The designed ageing model aims at providing the control system with reliable information about the actual status of the battery. A case study on degradation and ageing of a battery which is used in the modular PV/diesel/battery hybrid system installed on the island of Kythnos in Greece is introduced.

Furthermore, an advanced control concept based on a novel rule-based algorithm is developed. The introduced control concept optimizes the supply-side energy management. Upon pre-selected control settings and actual system conditions, the control decides for the optimal control strategy and generates highly optimized energy dispatch decisions. Moreover, based on the information provided by the fuzzy ageing estimation model, the developed control concept is able to improve the overall system performance, especially battery operating conditions and the diesel generator performance.

To investigate the technical and economic feasibility of both the developed control concept and the ageing estimation process, an object-oriented simulation tool has been developed by using the programming language MATLAB/Simulink®. The case study is carried out for a location called “Borg Al-Arab”, which is situated on the north coast of Egypt. Subsequently, several simulation outcomes that represent the interaction between the size of the back-up generator and the battery lifetime and between the operation control and the overall system performance are investigated. Moreover, the simulated performance criteria of the system designed for Borg Al-Arab are compared with results obtained from other similar research projects.
Zusammenfassung


Mit Hilfe der Fuzzy Logik wird ein Verfahren zur Schätzung der Batteriealterung entwickelt, das den gemessenen Strom, die Spannung und die Temperatur der Batterie nutzt, um die Hauptdegradationsmechanismen und deren dynamischen Einfluß auf die Alterung der Bleibatterien zu quantifizieren. Das entwickelte Alterungsmodell hat das Ziel, der Betriebsführung online zuverlässige Daten über den Batteriezustand zu liefern. Basierend auf verfügbaren Messergebnissen wird eine Fallstudie für die Entwicklung der Batteriealterung im modularen PV/Diesel/Batterie Hybridsystem vorgestellt, das auf der griechischen Insel Kythnos installiert wurde.


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Appendixes (A, B, C and D)
1 Introduction

1.1 Hybrid system technology for sustainable electrification

Energy represents a basic drive for the economic and social development of a country. However, one third of the world population, living in developing and threshold countries, has no access to electricity. These people mostly live in remote and rural areas with low population density, lacking even the basic infrastructure. Accordingly, utility grid extension is not a cost-effective option and sometimes technically not feasible. Therefore, it is imperative to look for sustainable (i.e. cost-effective, environmentally benign and reliable) sources of energy for the development of these regions. Using locally available alternative energy resources (e.g. PV, wind, etc.) and implementing modularly expandable and task-oriented system concepts guarantee cost-effective and sustainable resources of energy, especially for remote and rural areas [Kleinkauf-94].

For rural and remote areas the generation of AC-compatible (i.e. electricity with nearly constant voltage and frequency) power supply can be very expensive. Typically this is achieved using diesel generator sets which have low investment cost but high running costs, particularly for the smaller units. Generation costs are increased by the unsuitability of such units for meeting the peak loads encountered in small communities with low consumer diversity and similar social habits. Therefore, systems are often over-dimensioned by installing multiple diesel units in order to compensate the peak periods, causing low efficiency and higher maintenance costs. The first hybridization step is taken by adding a PV or a WTG to such conventional electricity generation systems which may increase these operation problems. As the power has to be supplied continuously, the diesel must always run to meet any instantaneous deficit caused by load increase or renewable resource fluctuations. In this hybrid system, the renewable converter serves as fuel saving unit. Nonetheless, renewably generated power serves to decrease further the average loading ratio of the diesel plant, and consequently increased maintenance costs may outweigh fuel savings. The addition of some kind of energy storage partially solves the problem of the diesel by enabling diesel shutdown when the generated renewable energy plus the stored energy is higher than the demand [Schmid-97]. Moreover, integration of a storage medium enhances the renewable energy usability.

The global effect of green house gases and the need for sustainable energy supply enforces the development of power supply structures that are based mainly on renewable resources. Hence, renewable converters, especially in remote and rural areas, are not considered as fuel saving units any more but as the basic power generators, and the diesel sets are used as back-up for increasing the supply reliability. This justifies the combination of different forms of locally available renewable energy resources (e.g. solar irradiation, wind and hydropower, etc.) to form hybrid systems.
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Figure 1.1: Classification of power supply technologies for electrification with RES, primary energy resources, power ranges, state and trend [Kleinkauf-00a]

For using locally available and naturally decentralized energy resources hybridization becomes a promising technology. The nature of hybridization is mainly based on the special features and economic potential of various energy conversion processes and on the power range (compare Figure 1.1). From this figure we can notice the application spectrum of various energy resources for electrification purposes throughout the total power range. Hybrid system technology mainly covers the autonomous and island grid of small and medium power ranges (from stand-alone systems to isolated grids). Moreover, hybridization can expand to include regional and trans-regional grids. In this large-scale hybridization a compensation of the available energy generated by for example a wind park in Spain or Morocco with a hydropower plant located in Norway to cover a trans-regional grid demand is possible [Kleinkauf-01]. However, this large scale of hybridization is out of the scope of this thesis.

The small and medium hybridization classes ideally match the rural and remote areas in most developing countries. The usual hybrid system configurations in these classes use the locally available solar irradiation and/or wind energy (the PV and wind turbine converters) in combination with storage media and fossil fuelled back-up generators.

Different decentralized hybrid systems based mainly on PV and/or WTG combined with battery storage and auxiliary diesel generator have been installed and operated in different climates and applications for several years (refer to [Timilsina-01], [Schmid-00], [Strauss-00], [Aulich-98], [Bopp-98] and [Sayigh-97]). The main purpose of these stand-alone hybrid systems is to supply electricity to
remote telecommunication stations, mountain huts, private houses, isolated farms, and villages.

1.2 Problem formulation

The integration of different types of energy converters (e.g. PV, wind and diesel) and storage media in the hybrid system has resulted in complex supply structures. Accordingly, appropriate design, operation, maintenance, and expansion strategies are needed in order to realize a cost-effective power supply option. Long-term investigations reveal that the vast majority of these systems needs optimized operation and maintenance strategies. The familiar expression that decentralized PV-systems are maintenance-free power suppliers is valid only for the solar converter. All other components require repairs, regular maintenance and replacement works, and post-installation improvements, as can be seen in Figure 1.2. In this figure, the average probability of malfunctions per component and year are illustrated for around 26 stand-alone hybrid systems [Bopp-00]. In general, system malfunctions are due to components failure (ageing reasons). About half the malfunctions noticeably limit the electricity supply. For newly installed systems, power conditioning equipment has become much more robust due to its technological development. However, some other components such as the battery still suffer from operation problems which still impair the dissemination of renewable systems.

The application of renewable hybrid system technology has to be market competitive for energy generation. In other words, it should be a technically reliable and cost-effective option to the consumer. These two criteria depend on the system configuration (i.e. type and size of each unit used to construct the hybrid system) and the control strategy that operates this configuration. Moreover, the energy production cost is also constructed from these two criteria, as can be

![Figure 1.2: Average frequency of failure per system component and year [Bopp-00]](image)
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seen in Figure 1.3. The first part of the life cycle cost function is the investment cost which depends on the system configuration and its consequent constructions, installations and montages. The second part comprises the operation and maintenance costs which depend on the component type and on the control strategy that operates the system.

However, a complex structure like a hybrid system with its multi-converters and storage is controlled via a hardware unit defined as the supervisory controller. This controller includes algorithms of specific operation and security functions which direct the behavior of each component during different situations. The consequences of these control actions are called an energy management strategy. Via this strategy the diesel engine is switched on or off, the diesel generator is loaded (e.g. to supply a part of the load) and the battery charged, discharged or left in open voltage mode which depends on the control settings and the system energy availability. Moreover, the control strategy has to consider many constraints such as the components operation boundary conditions, system requirements and user needs. That makes the control a sophisticated part during system design and a basic function that influences the energy production costs.

Almost all small and medium size renewable energy systems (low voltage range 230/400V) for decentralized electricity generation are equipped with a Pb-battery storage. The batteries in these stand-alone systems are the most sensitive equipment and often operate under severe conditions (such as successive charge/discharge and long periods under deep and partial discharge conditions) [Schmid-99]. Therefore, the battery lifetime in PV stand-alone systems is within 2-4 years which is very short if it is compared with the manufacturer-defined lifetime of the PV generator which has a lifetime of approximately 20 years. Moreover, the share of the battery in the investment costs of these decentralized systems is about 20%. However, its share in the life cycle costs of the system, based on 20 years project lifetime, is between 40% to 60%. Consequently, the energy production cost is often high, and the dissemination process of these renewable systems has not yet reached the desired sustainable and social requirements.

The back-up generator is another main component in the decentralized renewable systems if higher supply reliability is to be ensured. However, problems concerning frequent low loading ratio and frequent start/stop increase the fuel consumption and reduce the system reliability. Systems with incorrect component sizes and primitive control concepts result in frequent start/stop of the engine and frequent running at partial load conditions and, subsequently, low operating lifetime of the engine, higher maintenance costs and lower supply reliability. All these are reasons for higher €/kWh.

Therefore, it is necessary to operate the supply structure with optimized control strategies that extend the components lifetime and operate the diesel generator in its most efficient load range. Furthermore, it has to ensure cost-effectiveness
of the energy generation and high energy availability. A lack of information about the internal status of the battery such as acid stratification or the status of other degradation mechanisms usually hinders the execution of suitable control decisions (e.g. charging/discharge or electrolyte circulation phase). Continuous disconnecting of the battery to get information about its state of health or installing sophisticated measurement equipment are not useful solutions, neither technically nor financially. Frequent disconnecting of the battery can lead to its damage because of its sensitivity, and the necessary equipment and scales for investigating its state of health are often not available, especially in remote and rural regions. Moreover, transporting the battery to carry out such tests on it can lead to its damage and/or may reduce the supply reliability. Instrumentation to be installed within the battery is expensive and technically dangerous. Accordingly, another process to estimate the battery ageing and its state of health without disconnection from the system is essential. Furthermore, a suitable control concept that improves the performance of the decentralized hybrid system is required.

1.3 Research objectives and methodology

As illustrated in the previous section, there is a need to optimize the design (i.e. operation and sizing) of decentralized renewable hybrid systems. Accordingly, the system reliability and energy costs can be improved.

1.3.1 Objectives

The objectives of this thesis are:

- Development of an efficient procedure that estimates the ageing and state of health of the battery online (i.e. without disconnecting the battery from the system).
The task of this procedure is to supply the control strategy with the actual information about the state of health and ageing of the battery, by means of accurately selected parameters.

- Development of a practically applicable operation control concept which is based on novel functions and rules that takes into consideration present and the expected conditions of the system components, and generates the most efficient control decisions under any operating circumstances.

Figure 1.4 overviews the objectives and their interconnection, and it illustrates the necessary mathematical and knowledge-based tools to achieve the research aim. Optimizing the battery operating conditions and enhancing the hybrid system performance are considered to be a primary aim for this thesis.

In this work, the interdependency among system configuration, sizing and operation control of hybrid systems is taken into account. Moreover, constraints imposed on the operation of different generators are used to generate set values that are used by the control algorithm to generate optimum energy dispatch decisions. An object-oriented modeling technique is used to simulate the system components. Moreover, different qualitative criteria are selected in order to evaluate the designed system performance, and upon them design optimization can be carried out. In this thesis we will concentrate mainly on hybrid systems consisting of PV/WTG/diesel/battery.

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**Figure 1.4:** From the modeling to the design of hybrid systems, research procedure and methodology
1.3 Research objectives and methodology

1.3.2 Tools

The methodology and sequence followed in order to carry out this thesis are described in Figure 1.4. Three tools are used to develop the objectives of this work:

- **Mathematical modeling**: It is used to simulate the behavior of hybrid system components (PV/wind/diesel/battery). Each component is modeled by a group of parameterized mathematical equations. Based on the component type and characteristics, the model parameters are adjusted and verified. Also, mathematical tools are used to model the quality evaluation criteria of the system performance.

- **Fuzzy Logic**: The core of the thesis is to implement fuzzy logic knowledge-based methodology to develop an reliable procedure which estimates the battery ageing. Fuzzy logic uses available experience and know-how which is gathered from operating, testing and analyzing batteries in different applications in order to come out with a new procedure that considers the complex electrochemical behavior of the battery.

- **Statechart**: This is a methodology based on an integrated set of diagrammatic languages for modeling object-oriented systems, and it is implemented to develop the operation control concept. The State Machine is an event-driven (reactive) system which allows a modular and hierarchical and thus flexible specification of the operation control. Through well-defined state and mode-transition of the hybrid system the intuitive mixing of different modes of operation becomes possible.

Based on the developed ageing process and the control concept as well as with the support of the deduced system operation constraints, a simulation environment is developed. Later on, this simulation program is used to investigate the developed concepts and processes. It is implemented to optimize the design and performance of decentralized hybrid systems.

1.3.3 Work procedure

The work procedure in this thesis is carried out according to the following sequence:

In chapter 2, different hybrid system topologies and the concept of modularization and standardization are reviewed. Moreover, some quality criteria for evaluating the system performance are introduced. Components power conversion, control and their interrelation with the system supervisory control are overviewed. Special attention is given to the conversion efficiency and emissions of the back-up generator. Some fundamental definitions and operation characteristics of the battery are introduced. Finally, different costs of the components and their dependency on the system configuration and mode of operation are reviewed. This chapter is considered as a basis for Chapter 4 and 5.
In chapter 3, experience gained from operating lead-acid batteries under different conditions and applications, especially in PV systems, is analyzed. Measures to improve battery lifetime are also deduced. Different forms of energy losses in the battery are investigated. Reversible and irreversible degradation mechanisms are described. Furthermore, the most important mechanisms (acid stratification, corrosion and sulfation) are investigated. Factors influencing their development are elaborated, and their effect on the battery ageing is quantified. This chapter serves as main know-how and experience to build the ageing model in Chapter 4.

A knowledge-based model to estimate the battery ageing is developed in Chapter 4. Fuzzy-logic is implemented to model the complex process of battery ageing. The ageing model structure and fuzzy variables and membership functions of each degradation mechanism are developed. Moreover, validation data of the ageing model and different results are described for an OPzS lead-acid battery. This chapter is used to supply Chapter 5 with necessary parameters quantifying the battery actual state of health and ageing of the battery.

The core of Chapter 5 is the development of an advanced operation control concept for reliable and sustainable renewable energy systems. Hence, state of the art and trends in hybrid systems control and energy dispatch decisions are described. Besides the parameters gained from the ageing model, other necessary control measures are implemented to develop an advanced operation control algorithm. The Statechart technique is used as a platform in order to formulate the flexible control strategy.

In Chapter 6 a hybrid system simulation tool which implements object-oriented technique for modeling individual components is built. The simulation tool includes also the developed battery ageing procedure and the developed advanced control concept. The commercially available programming language MATLAB/Simulink® and its toolboxes are used as a platform to develop the simulation tool. In addition to the technical modeling, financial is integrated in the program. The input data type and format as well as the output performance parameters are described.

In Chapter 7 a case study which is based on real weather and load data for a specific location called “Borg Al-Arab” is simulated. Different control strategies and their influence on the system quality criteria are compared with the developed one. Furthermore, trade-off sizing methodology is used to design the most economic and consumer satisfactory hybrid systems for . Sensitivity analysis is briefly introduced for some important design parameters in order to measure the sustainability of the chosen design under uncertainties.

Chapter 8 concludes the most important characteristics and results of this research thesis. Furthermore, perspectives for future scientific research areas related to this investigation are overviewed.