OPTIMISATION OF HYBRID ENERGY SYSTEMS SIZING AND OPERATION CONTROL

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A Dissertation
presented to the University of Kassel
in Candidacy for the Degree of
Dr.-Ing.

October 1998

Die Deutsche Bibliothek - CIP-Einheitsaufnahme

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ISBN 3- 933146-19-4

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Abstract

This thesis focuses on the development of a new approach for the sizing and operation control of a hybrid system with the goal of minimising life cycle costs per kWh and meeting required supply reliability. The optimisation method employed makes use of genetic algorithms. Genetic algorithms do not require gradient calculations. Therefore the hybrid system can be modelled with a high degree of accuracy considering the highly complex workings of actual systems, while still keeping computation time at reasonable levels.

Optimisation algorithms change the values of so-called decision variables of an underlying model in such a way as to optimise the resulting value of the model's objective function. In this thesis an objective function is developed whose value for a specific hybrid system design serves as a classification of merit for the design. The objective function is a combination of life cycle costs per kWh and penalty costs per kWh for unmet demand. In addition, a model for hybrid systems is developed through a precise power flow description of the energy transmission in a hybrid system.

The calculation of the power flow depends on the prior determination of the values of the model's decision variables, which consist of component sizing variables and control setting variables. Where possible, the number of variables is reduced through substitution with characteristic system and component operation equations.

The remaining operating decisions encountered in the power flow are battery and diesel generator outputs. Once either the battery or the diesel generator output is chosen, the other output level and therefore the power flow is determined automatically. However, independent of which component output value is computed, this needs to be carried out at every single time instant during system operation. The number of decision variables to be optimised would then become very high. Therefore, control settings are introduced that indicate the level of battery state of charge and unmet demand at which either the value for the battery output or the diesel generator output is determined first. The computation of the other output value and the complete power flow can then follow automatically. Another advantage of optimising the control settings instead of component outputs at each time instant is that the values for the control settings can be readily implemented in actual systems through the corresponding adjustments of system controllers.

The value of a control setting is determined in the genetic algorithm, together with the values of the sizing variables, and then remains constant during the simulation of the model until it is changed in the next iteration of the genetic algorithm. The algorithm converges when the values of the decision variables, the model's performance and its merit of design do not improve significantly anymore.

The algorithm has been implemented in the computer language MATLAB©. The simulation runs with MATLAB© are useful to present the algorithm as a new and improved tool to use in optimising hybrid system design. MATLAB© is a slow computing language that is not using computer hardware resources in an optimal way, however, it allows flexible programming for research purposes.

To verify the effectiveness of the approach, the developed algorithm is applied to two case scenarios for typical farming demand profiles and for typical remote sites in South Africa for which the use of hybrid systems can be considered. The results are meaningful and give insight into the relation between system operation and sizing and costs.

The results are also compared with other approaches, namely the rule-of-thumb method, the Ah method, spreadsheet methods, the performance simulation tool HYBRID2 and with data from actually installed systems. It can be seen that the recommended designs and the calculated costs by the algorithm are realistic.

Zusammenfassung

Diese Dissertation befaßt sich mit der Entwicklung einer neuen Strategie zur Bestimmung von optimalen Systemgrößen und einer optimalen Betriebsführung für Hybridsysteme, mit dem Ziel, die Gesamtkosten pro kWh zu minimieren und die erforderliche Zuverlässigkeit der Elektrizitätsversorgung bereitzustellen. Die verwendete Optimierungsmethode benutzt genetische Algorithmen. Genetische Algorithmen erfordern keine Berechnung der Gradienten. Daher kann das hybride System unter Berücksichtigung seiner sehr komplexen Funktionsweise mit einem hohen Grad von Genauigkeit modelliert werden, wobei dennoch die rechnergestützte Berechnungszeit in einem vernünftigen Rahmen gehalten wird.

Optimierungsalgorithmen ändern die Werte der sogenannten Entscheidungsvariablen eines zugrundeliegenden Modells so, daß der resultierende Wert der Modellzielfunktion optimiert wird. In dieser Arbeit dient der Wert der entwickelten Zielfunktion für ein entworfenes Hybridsystem als Maß für die Verwendbarkeit des Design. Die Zielfunktion ist eine Kombination von Annuitätenkosten pro kWh und Strafkosten pro kWh für nicht gedeckte Last. Außerdem wird ein Modell für die genaue Beschreibung des Energieflusses im hybriden System entwickelt.

Die Berechnung des Energieflusses hängt ab von den Werten der Modellentscheidungsvariablen, welche aus Anlagengrößenvariablen und Betriebsführungsvariablen bestehen. Diese müssen vor Berechnung des Energieflusses feststehen. Wo es möglich ist, wurde die Anzahl der Systementscheidungs-Variablen reduziert durch Ersetzung mit charakteristischen Gleichungen für das System und für die Komponentenbetriebsführung.

Die verbleibenden Betriebsführungsentscheidungen in der Energieflußbeschreibung sind die Batterie- und Dieselgeneratorströme. Sobald entweder der Batteriestrom oder der Dieselgeneratorstrom festgelegt ist, kann der andere Komponentenausgangsstrom und daher auch der Energiefluß automatisch bestimmt werden. Unabhängig davon, welcher Komponentenausgang zuerst festgelegt wird, muss dies zu jedem einzelnen Zeitpunkt während der Systembetriebsführungsimulation erfolgen. Die Anzahl der Entscheidungsvariablen, die optimiert werden müssen, würde dann sehr hoch. Daher werden sogenannte Betriebs- oder Regeleinstellungen eingeführt, die den Batterieladezustand und die Größe des nichtgedeckten Verbrauchs angeben, bei dem entweder der Wert für den Batteriestrom oder den Generatorstrom zuerst bestimmt wird. Die Berechnung des jeweils anderen Stromes und die komplette Energieflußberechnung folgen dann. Ein weiterer Vorteil, die Regelungseinstellungen statt der Komponentenausgänge zu optimieren, die zudem für jedes Zeitintervall optimiert werden müßten, ist, daß die Werte für die Betriebsführungsseinstellungen im realen System durch die korrespondierende Einstellung der Systemregelung einfach implementiert werden können.

Der Wert einer Betriebsführungseinstellung wird im genetischen Algorithmus bestimmt und optimiert, zusammen mit den Werten für die Komponentengrößen. Der Wert einer Betriebsführungseinstellung bleibt konstant während der Simulation des hybriden Systemmodels, bis er in der nächsten Iteration des genetischen Algorithmus' geändert wird. Der Algorithmus konvergiert, wenn die Werte der Entscheidungsvariablen, d.h. die Betriebsführung und die Systemauslegung, sich nicht mehr beträchtlich ändern.

Der Algorithmus ist in der Computersprache MATLAB implementiert. Die Simulationen mit MATLAB sind nützlich, um den Algorithmus als ein neues und verbessertes Verfahren zu präsentieren, das verwendet werden kann, um das Design von hybriden Energiesystemen zu optimieren. MATLAB ist eine langsame Computersprache, die Computer Hardware Ressourcen nicht optimal nutzt. Es erlaubt jedoch eine flexible Programmierung für Forschungsvorhaben. Um die Effektivität des Verfahrens zu verifizieren, wurde der entwickelte Algorithmus auf mehrere Fallstudien für typische Farmverbrauchsprofile in entlegenen Gebieten in Südafrika, die für den Gebrauch von hybriden Systemen geeignet sind, angewendet. Die Ergebnisse sind aussagekräftig und geben Einblick in die Abhängigkeit zwischen Systembetriebsführung, Komponentenauslegung und Kosten.

Die Ergebnisse wurden zusätzlich mit anderen Designmethoden verglichen, nämlich mit der Daumenregelmethode, der Ah Methode, einer eigens entwickelter Spreadsheet Methode, der Betriebssimulations-Software HYBRID2 und mit tatsächlich installierten Systemen. Es konnte bestätigt werden, daß die von dem Algorithmus empfohlenen Systemdesigns und die berechneten Kosten realistisch sind.

Acknowledgements

I would especially like to thank my husband Frank for his important contributions and continuous support.

I want to especially thank Professor Schmid for supervising my thesis and his support throughout the years, and Professor Hanitsch for finding the time to co-supervise it.

My special thanks go to the Department of Minerals and Energy of South Africa, and especially to Dr J Opperman at the DME, for the important and constructive support of the presented work. I am very grateful to a number of other very helpful members of the DME, namely Mr Andre Otto, Ms Thavy Pillai, Dr T Surridge, Dr J Basson, Ms van Collern and Dr I Kotze.

Furthermore I would like to thank Dr Chris Marrison, presently at Oliver, Wyman & Company New York, for his contributions and discussions of the cost-benefit analysis methodologies.

My thanks go further to the village power team at NREL, namely Larry Flowers, Jim Green, Tony Jimenez, Dennis Barley, Peter Lillienthal, Steve Drouillhet, Dave Corbus, Rick Holz, April Allerdice, Debbie Lew, and many others for the discussions and exchange. And I would like to thank Dr Doug Arent for facilitating the discussions with NREL.

I would also like to thank the students who worked with me, namely Sabine Piller, Ahilan Kailasanathan, Clinton Slabbert, Ian Marchall, Ingo Knoblich, and Peter Weber. I would also like to thank Professor Schaffrin at the Renewable Energy Section of the Fachhochschule Konstanz and Marcus Rehm from the Renewable Energy Systems Group at the Fraunhofer Institut Freiburg for the co-operation. A further institute I am grateful to is the hybrid systems group under Dr van Dijk at the University of Utrecht.

Thanks also go to Edward van Kuik for many discussions and creative contributions.

I am grateful to the South African PV industry, especially Reinhard Otto, Conrad van Roerden and many others, and to many of the US hybrid systems companies for sharing their experiences with me.

Further thanks go to the National Hybrid Systems Workgroup of South Africa with whom I could share many ideas and from whom I learned a lot, namely Gareth Dooge, Lizelle Kok, and Minnesh Bipath (ESKOM), Mike Witherden and Gavin Gradwell (Mangosuthu Technikon), Andries van der Linden (Port Elisabeth Technikon), Clive Norton and Steve Szewczuk (CSIR), Dr Deon Stassen (DBSA) and again Dr Opperman (DME).

I would also like to express my thanks to the DAAD (the German Academic Exchange Service) and the EDRC (Energy and Development Research Centre) for financial contributions in form of bursaries.

Finally, I would like to thank my parents and my grandmother for their support.

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Frequently used Nomenclature

Symbol	Meaning	Unit
$\%_{Max(Min)}$	Percentage battery state of charge	%
$\%ofCC_{Bat}$	Percentage of capital costs added for installation and bos parts for battery banks	%
$\%ofCC_{D,size,i}$	Percentage of capital costs added for installation and bos parts for diesel generator type i	%
$\%ofCC_{PV}$	Percentage of capital costs added for installation and bos parts for PV	%
$\%ofCC_{WT}$	Percentage of capital costs added for installation and bos parts for wind turbines	%
η	Battery charging efficiency	%
σ	Selfdischarge rate	%
η_{losses}	Efficiency losses due to conversion losses, wire losses, battery cycling losses	%
c	Charge/discharge indicator	
$corr_{Factor}$	Correction factor to account for increases in fuel needs during start-up	
$Cost_{Bat}$	Battery cost according to size and type of battery	ECU
$Cost_{Dies}$	Diesel generator cost according to the size of the diesel generator type	ECU
$Cost_{PV}$	PV panel cost according to the size of the PV panel type	ECU
Costs	Vector of component costs	ECU
$Cost_{WT}$	Wind turbine cost according to the size of the wind turbine type	ECU
$Demand_{Wh/day}$	Average demand in Wh/day	Wh/day
$eff_{bc}(t)$	Efficiency of battery charger	%
$eff_{inv}(t)$	Efficiency of inverter	%
$FixedCosts_{Bat}$	Added fixed costs accounting for installation and BOS parts, Battery	ECU
$FixedCosts_{Dies}$	Added fixed costs accounting for installation and BOS parts, Diesel	ECU
$FixedCosts_{Diesel,type,i}$	Added fixed costs accounting for installation and BOS parts for diesel generator type i	ECU
$FixedCosts_{perYear,Bat,i}$	Fixed operaion costs arising during battery type i operation each year	ECU
$FixedCosts_{perYear,Dies,i}$	Fixed operation costs arising during diesel generator, type i, operation each year	ECU
$FixedCosts_{perYear,PV}$	Fixed operaion costs arising during PV operation each year	ECU
$FixedCosts_{perYear,WT,i}$	Fixed operaion costs arising during wind turbine type i operation each year	ECU
$FixedCosts_{PV}$	Added fixed costs accounting for installation and BOS parts, PV	ECU
$FixedCosts_{WT}$	Added fixed costs accounting for installation and BOS parts, Wind	ECU
f_{MM}	Mismatch factor for different PV panel current outputs	
Fuel Cost/ Litre	Cost of fuel in ECU/litre	ECU/litre
fuel_costs	Fuel cost measure	ECU
$Hours_{sunshine/day}$	Average number of estimated sunshine hours per day	hour
$I_{ACBus,o/p}$	AC bus current output	Ampere
$I_{ACload}(t)$	AC load current	Ampere
$I_{ACsupply}(t)$	Current arriving at AC load	Ampere
$I_{bat}(t)$	Battery current	Ampere
$I_{bat,ch}(t)$	Charging current	Ampere

Symbol	Meaning	Unit
$I_{bat,dis}(t)$	Discharging current	Ampere
$I_{bat,max,ch(dis)}(t)$	Maximum battery charging (discharging) current at time t	Ampere
$I_{BatsysCh(Dh)}(t)$	Current with which system can charge battery (discharge current system requires)	Ampere
$I_{bc\text{-}DC}(t)$	Battery Charger DC output current	Ampere
$I_{BC\text{-}i/p}(t)$	Battery charger input current	Ampere
$I_{bcmean}(t)$	Maximum efficient battery charger output current	Ampere
$I_{BC\text{-}o/p}(t)$	Battery charger output current	Ampere
$I_{DCBus}(t)$	DC bus current	Ampere
$I_{DC\text{-}bus}(t)$	DC bus current	Ampere
$I_{DCload}(t)$	DC load current	Ampere
$I_{DCSources}(t)$	DC current generated from the DC sources	Ampere
$I_{DCsupply}(t)$	Current arriving at DC load	Ampere
$I_{Demand,Daily}(t)$	Daily demand at time t	Ampere
$I_{diesel}(t)$	Diesel current	Ampere
$I_{Diesel,Array,Bus,k}(t)$	Diesel generator array output current on bus k at time t	Ampere
$I_{Dieselmax,i}$	Maximum possible output current of diesel generator type i	Ampere
$I_{Dieselmax,i,Bus,k}$	Maximum possible output current of diesel generator of type i on bus k	Ampere
$I_{IndBat,i}(t)$	Battery current of an individual battery of battery bank i	Ampere
$I_{inv}(t)$	Inverter input current	Ampere
$I_{Inv\text{-}i/p}(t)$	Inverter input current	Ampere
$I_{invmean}(t)$	Maximum efficient inverter output current	Ampere
$I_{Inv\text{-}o/p}(t)$	Inverter output current	Ampere
I_{max}	Max possible battery current	Ampere
$I_{max,Ch(Dh)}$	Maximum charging (discharging) current) as given by manufacturer	Ampere
$Imbalance_{AC}(t)$	AC over or under supply	Ampere
$Imbalance_{DC}(t)$	DC over or under supply	Ampere
$InitCost_{Diesel}$	Overall initial costs incurred by the diesel generator installation	ECU
$InitCost_{Diesel,type,i}$	Diesel generator initial costs of type i	ECU
$InitCost_{PV}$	Overall initial costs incurred by PV installation	ECU
$InitCost_{WT}$	Overall initial costs incurred by the wind turbine installation	ECU
$InitCost_{WT,type,i}$	Wind turbine initial costs of type I	ECU
$I_{OtherRESources\text{-}AC}(t)$	AC output current from other renewable energy sources at time t	Ampere
$I_{OtherRESources\text{-}DC}(t)$	DC output current from other renewable energy sources at time t	Ampere
$I_{PV,Array}(t)$	PV array current output at time t	Ampere
$I_{PV,Array\text{-}AC}(t)$	AC output current from PV array at time t	Ampere
$I_{PV,panel}(t,x_{Size,Type,PV})$	PV panel current output at time t depending on panel type	Ampere
$I_{re}(t)$	Renewable energy current	Ampere
$I_{RE\text{-}AC}(t)$	Overall AC current from renewable energy sources at time t	Ampere
$I_{RE\text{-}DC}(t)$	Overall DC current from renewable energy sources at time t	Ampere
$I_{WT,Array,Bus,k}(t)$	Wind turbine array output current on bus k, i.e.in DC or AC	Ampere
$I_{WT,Array\text{-}AC}(t)$	AC output current from wind turbine array at time t	Ampere
$I_{WT,Array\text{-}DC}(t)$	DC output current from wind turbine array at time t	Ampere
$I_{WT,i,k}(t)$	Individual wind turbine current output of wind turbine type i on bus k	Ampere
k	Bus k, k equals mainly AC or DC	
Litres (:)	Function relating the diesel generator output power to its fuel consumption	
LitresUsed	Fuel used during the time interval T in litres	litres
n	Year n	year
$n_{Bat,series}$	Number of batteries in series	
no	Vector with numbers of devices	
no^*	Vector with optimal number of devices	
NOofBatBanks	Number of different battery types available for the optimisation	

Symbol	Meaning	Unit
	from a pool of batteries	
NOofBC	Number of different battery chargers available for the optimisation from a pool of battery chargers	
NOofBusTypes	Number of different DC and AC busses in the system	
NoofDieselTypes	Number of different diesel generator types available for the optimisation from the diesel generator pool	
NOofInv	Number of different inverter available for the optimisation from a pool of inverters	
NOofWTtypes	Number of different wind turbine types available for the optimisation from a pool of wind turbines	
$n_{PV,series}$	Number of PV panels in series	
$Opas\%ofCC_{perYear,Bat,i}$	Percentage of capital costs arising as battery type i operation cost each year	%
$Opas\%ofCC_{perYear,Dies,i}$	Percentage of capital costs arising as diesel generator, type i, operation cost each year	%
$Opas\%ofCC_{perYear,PV}$	Percentage of capital costs arising as PV operation cost each year	%
$Opas\%ofCC_{perYear,WT,i}$	Percentage of capital costs arising as wind turbine type i operation cost each year	%
OpCo	Operating cost	ECU
$Opcost_{Bat}(n)$	Overall battery operation costs after n years	ECU
$Opcost_{Diesel}(n)$	Overall diesel generator operation costs after n years	ECU
$Opcost_{PV}(n)$	Overall PV operation costs after n years	ECU
$Opcost_{WT}(n)$	Overall wind turbine operation costs after n years	ECU
$P_{BC-i/p}(t)$	Battery charger input power	Watt
$P_{BC-o/p}(t)$	Battery charger output power	Watt
$P_{diesel}(t)$	Diesel genset output power	Watt
PeakDemandPower	Maximum demand in W required by the application	Watt
$P_{i/p}(t)$	Battery charger input power	Watt
$P_{inv-i/p}(t)$	Inverter input power	Watt
$P_{inv-o/p}(t)$	Inverter output power	Watt
$P_{max,diesel}$	Maximum diesel genset output power	Watt
$P_{o/p}(t)$	Battery charger output power	Watt
$Power_{PV,Array}$ (t)	PV array power output at time t	Watt
$P_{WT,Array}(t)$	Wind turbine array output power at time t	Watt
r	Discount rate	%
R(n)	Discount factor for the same yearly expenditure which occurs for n years	
$Replacementcosts_{Diesel}$	Overall diesel generator replacement costs	ECU
$replacementcosts_{PV}$	Overall PV replacement costs	ECU
$replacementcosts_{WT}$	Overall wind turbine replacement costs	ECU
$Replacement_{year,PV}$	Lifetime of the PV panels in number of years	
$Replacement_{year,WT,i}$	Lifetime of the wind turbine type i in number of years	
$Repl_{year,Bat}$	Lifetime of the batteries in number of years	
$Repl_{year,Dies,i}$	Lifetime of the diesel generator type i in number of years	
$SOC\%_1$	Control setting 1: (both inverter output and diesel generator output can cover the load): If battery state of charge is below $SOC\%_1$, then prefer the diesel generator to cover the load, else prefer the inverter output	%
$SOC\%_2$	Control setting 2: (neither inverter output nor diesel generator can cover the load alone): If the battery state of charge is below $SOC\%_2$, then NORMAL INVERTER : allow the diesel generator to supply the AC load through the inverter (together with the DC supply) if this lowers unmet demand, else don’t allow this option and choose lowest unmet demand supply option (either inverter output or diesel generator output supplies load)	%

Symbol	Meaning	Unit
	PARALLEL INVERTER: prefer the diesel generator to cover load and take any additional energy from the inverter output, else the other way round	
$SOC(t)$	State of charge	Ah
$SOC_{crit}(t)$	Critical state of charge	Ah
$SOC_{max}(t)$	Maximum state of charge	Ah
$SOC_{min}(t)$	Minimum state of charge	Ah
t	Time instant t	hour
T	Length of time interval over which the assessment/simulation is carried out	hour
t_0	Starting time	hour
type	Vector of component types (PV,wind,etc)	
Type	Matrix with type on 1st diagonal	
$type^*$	Optimal vector of component types	
U_{ac}	Nominal AC bus voltage	Volt
$U_{Bat,Nom,Bank,i}$	Nominal voltage of battery, bank i	Volt
$U_{Bus,k,Nom}$	Nominal voltage of bus k	Volt
$U_{Bus,Nom}$	Nominal bus voltage	Volt
U_{dc}	Nominal DC bus voltage	Volt
$U_{Panel,Nom}$	Nominal PV panel voltage	Volt
$U_{WT,i,Nom}$	Nominal voltage of wind turbine type i	Volt
$W_{expected,PVpanel}(t)$	Expected PV panel output power	Wp
x	Vector of decision variables	
x^*	Optimal decision vector	
x_{bat}	Battery charge/discharge decision as percentage of maximum possible battery current at time t	%
$x_{Bat,parallel,Bank,i}$	Number of battery strings of type i	
$x_{Diesel,i}(t)$	Output of diesel generator type i at time t as percentage of maximum possible nominal output power in W	%
$x_{Diesel,i,parallel}$	Number of diesel generators of type i installed in parallel	
x_{load}	Load management decision	%
$x_{PV,parallel}$	Number of PV strings in parallel	
$x_R(t)$	DC bus current routing	%
$x_{R,BC,j}$	Routing decision to battery charger j	%
$x_{R,Inv,j}$	Routing decision to inverter j	%
$x_{RD}(t)$	Diesel current routing	%
$x_S(t)$	Transfer switch position	%
$x_{size,Bat,Bank,i}$	Size of wind turbine type i	W_p
$x_{size,BC}$	Size of battery charger	Watt
$x_{Size,D,i}$	Size of diesel generator type i	W
$x_{size,Inv}$	Inverter size	W
$x_{Size,Type,PV}$	PV panel size of a certain PV panel type	W_p
$x_{Size,Type,WT,i,k}$	Size of wind turbine type i on bus k, i.e. DC or AC wind turbine size	W_p
$x_{sizeD,i}$	Nominal output power in W of diesel generator type i	W
$x_{WT,i,parallel,k}$	Number of wind turbine strings of wind turbine type i on bus k, i.e. Dc or ac strings	