THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Autonomous Power Systems based on Renewables
- On generation reliability and system control

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Göteborg, Sweden 2007

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ISBN 978-91-7291-908-2

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr. 2589
ISSN 0346-718X

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Chalmers Bibliotek, Reproservice
Göteborg, Sweden 2007

To family and friends

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Abstract

Today one billion people are living in non-electrified areas. A majority of the people are living in rural areas in developing countries where there are no possibilities, neither economical nor technical, for grid extension. Instead energy sources like wood and fossil fuels are used. However, these sources are not suitable due to environmental reasons and therefore electricity is favourable. Autonomous power systems are for that reason needed to secure a decent living standard and still preserving the environment.

To be able to study the availability of solar power for electricity production in rural areas a method for solar insulation simulation is proposed. The method is based on cloud coverage according to the Oktas-scale. Cloud coverage is often available due to its low demand on technical equipment during measurement. Since continuous data series are hard to find the model is based on transitions between different levels of cloud coverage. A stochastic model for wind speeds for electricity production based on quantified wind speed measurements is also proposed. The model is only dependent on the site-specific yearly mean value of the wind speed if a distribution of wind speeds from a location with a similar distribution is available. Other models used are for a weak constant flow-of-river and for storage. The load considered was industrial with its maximum during daytime.

The generation reliability of using only one production source was found to be low. Combinations of production sources or a storage capacity significantly improve the situation. Even if several different sources are used some over-capacity of power production is required.

Normally, the generation is cut down to control the frequency of a system. The generation is cut down to save fuel but in systems where

wasted. To limit the waste a method based on load frequency control of a frequency converter is proposed. Some new frequency converters are equipped with an active rectifier also voltage control can be implemented. A control design for voltage control is also proposed. Both the frequency and voltage control are tested through simulations and are verified in a laboratory environment. The behaviour of the frequency control as well as voltage control is even better as compared to normal control methods. It has been shown that both the frequency and voltage controllers can easily be implemented in the same off-the-shelf frequency converter.

Index Terms: Solar power, Wind power, Renewable energy, Stochastic models, Generation reliability, Rural areas, Developing countries, Island operation, Load control, Continuous Controllable Load (CCL), Frequency converters, Frequency control, Voltage control.

Acknowledgements

This project was funded by the Alliance of Global Sustainability (AGS), the Adlerbertska foundation and the foundation to the memory of R. J. Gust. Richert, which are gratefully acknowledged.

I would like the thank my supervisors Dr. Evert Agneholm and Prof. Math Bollen for all help and encouragement throughout the project. Additionally, I would also like to acknowledge Prof. Gustaf Olsson and Prof. Jaap Daalder who supported me. I would also like to thank Dr. Jörgen Blennow for inspiring me to become a Ph.D. student and his support since the first day at Chalmers.

I am very grateful to my colleagues for all the help and support. Particulary, Johan Andersson, Massimo Bongiorno, Magnus Ellsén, Ramona Huuva, Elisabeth Lindell, Dr. Stefan Lundberg, Lena Max, Dr. Yuriy Serdyuk and Prof. Torbjörn Thiringer both for the help with the work and creating a nice working atmosphere. It has helped me a lot during the tough times.

I would also like to thank Anders Toft for introducing me to the exciting world of electric power engineering.

During the project I made a trip to Tanzania and I would like to acknowledge Leif Andersson (SWECO) and his colleagues for all the support which made the trip a life long memory.

Henri Putto should be acknowledged for believing in the ideas and the support with the frequency converter even after my own programming.

Finally, I would like to thank my family and friends, especially my wife Susanna, for all the love and support throughout the project.

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Göteborg, Sweden
March, 2007

Contents

Chapter 1

Introduction

Imagine a life without electricity. No TV, radio and refrigerator or any of the other things that help us a normal day. However, this is the condition for of billions of people around the world. People are starving and have to walk several kilometers for fetching water. Developing countries have large problems and the problems are not only economical but also social and environmental.

Examples of environmental problems are deforestation, indoor pollution from cooking and contribution to the greenhouse effect by the use of fossil fuel. The economical problems are mainly due to the difficulties of commercial and industrial activities together with migration. Another problem is the need for electric light. It is very hard to read in the light of candles. The problem with education is mainly for adults since they have to study after the regular working day.

The world can probably not afford a development for these billions of people like the one that has taken place for the industrialised countries. In the beginning of the industrialisation the natural resources were spent without restraints, emissions were large and wastes were dumped. That is why a sustainable basic development is needed which is something that the developed countries have little, if any, experience of. However, a lot of knowledge and technical competence that has been developed in other parts of the world can be used to speed up the process.

Much research is going on in the area of harvesting sustainable energy sources. Unfortunately it is often focused on the developed part of the world, since that is where the financial resources are available. Research focusing on the problems for developing countries is needed because developing countries have their own problems and thereby their need for their own solutions. The problem with research is not isolated to the energy sector but also in other areas, like medicine and economics.

This project focuses on finding a feasible solution for electricity production. The proposed systems should be built as small isolated power systems but still be sustainable. The systems should be suitable for the size of a village and adapted to local conditions. The systems are thought to be combined with some kind of industrial activity. The combination is important to make the system both economically sustainable and socially accepted.

As energy sources the focus are on solar and wind since they are sustainable and the "fuel" is for free. To be able to calculate the energy production of solar panels the solar radiation needs to be studied. A problem in many developing countries is that hardly no solar radiation measurements are done because they demand expensive equipment. Therefore a model has been developed that is based on cloud observations. The observations should be done manually and therefore no equipment is needed. The model is also adapted to utilise low quality data.

For wind power another model was developed that also utilises low quality data. Even data from a site with similar weather conditions can be used as long as the annual mean value from the actual site is known. The model also includes adjustments to the height and the behaviour of a wind turbine.

A large problem with solar power is that no electricity is produced during night time and wind turbines do not produce any electricity when the wind is not blowing. Because of that the availability of the energy needs to be studied. The studies include not only the individual behaviour of sources but also combinations of them. Since the available sources are dependent on local conditions also combinations with small scale hydro power and/or a storage are investigated.

When a system is based entirely on solar and wind power sources an over capacity of the sources is needed since the sources are not always producing at maximum. On the other hand, there will sometimes be an overproduction of energy when too much energy is available. To control a power system the production and the consumption have to be equal at any moment and therefore the power needs to be controlled. Normally the generation is limited to control the system but then energy will be wasted. However, if the load is adjusted and takes care of the available energy less energy will be wasted. The problem with such a load is that it will be hard to predict when it will run or not. Therefore the load has to be connected when the surplus power is available, thus being quite independent on the operating time. An example of such a load is a water pump for irrigation purposes.

The challenge is to see how a sustainable increase of living standard for people can be done with off-the-shelf technologies. It is not only the environment that should be sustainable but also the financial and social development. All work has to start in the current conditions and be adapted to the people living today.

1.1 Main scientific contributions

Below the main contributions of the thesis are summarised:

- A stochastic model of solar power that is based on low quality cloud coverage observations has been developed.
- A stochastic model of wind power that can be used with low quality data has also

been developed.

- A frequency control method of an autonomous power system based entirely on renewables has been proposed. The method is based on a frequency converter controlled load (CCL). The method controls not only the frequency of the system but also utilises available over-capacity in the generation sources. The control method is shown to be faster than other more conventional frequency control methods.
- A voltage controlled method for an autonomous power system based on the use of a CCL has also been proposed. By utilising a state-of-the-art frequency converter the converter can be used for voltage control of the autonomous system. It has been shown that with only some small programming in the existing control program a voltage controller that fulfills the demands can easily be obtained.

1.2 Structure of the thesis

This thesis is written as a summary of eight papers. The main chapters are therefore kept brief to serve as an introduction and provide a background of the work. Details are found in the papers but conclusions are summarised. The chapters are:

Chapter 2 that discusses the background of rural electrification in developing countries with a focus on the differences between a developed and a developing country. As an example the conditions in Tanzania are studied.

Chapter 3 that reviews the generation and storage models that are used in the Chapter 4. The main models are stochastic models of solar and wind that can be based on low quality weather data.

Chapter 4 where generation reliability is studied, based on the models from Chapter 3. The studies are based on Monte Carlo-simulations and an industrial based load model. The influence of different configurations of production sources and storage capacities is investigated.

Chapter 5 that investigates the use of load control of autonomous power systems that are based entirely on renewables. The control system is based on a CCL that limits the waste of the over production of renewables that is needed for availability reasons. Both frequency and voltage control are studied by the use of a CCL.

Chapter 6 that summarises the conclusions of the work and suggests some interesting areas for future work.

1.3 List of Publications

The publications originating from this Ph.D. project are:

I **S. G. J. Ehnberg**, M. H. J. Bollen, "Simulation of global solar radiation based on cloud observations," *Solar Energy*, vol. 78, no. 2, pp. 157-162, Feb. 2005.

II **S. G. J. Ehnberg**, M. H. J. Bollen, "Reliability of a small isolated power system in remote areas based on wind power," in *Nordic Wind Power Conference (NWPC'04)*, Göteborg, Sweden, March 2004.

III **S. G. J. Ehnberg**, M. H. J. Bollen, "Reliability of a small power system using solar power and hydro," *Electric Power Systems Research*, vol. 74, no. 1, pp. 119-127, April 2005.

IV **S. G. J. Ehnberg**, M.H.J. Bollen, "Generation reliability of a small isolated power system entirely based on renewable sources," *General Meeting, IEEE power engineering society*, Denver, Colorado, USA, June 2004.

V **S. G. J. Ehnberg**, E. Agneholm, "Maximal use of renewables in small isolated power systems," in *Cigre Symposium on Power systems with dispersed generation*, Athens, Greece, April 2005.

VI **S. G. J. Ehnberg**, E. Agneholm, "Reverse Motor Control for CCLs in AC Hybrid Minigrids," in *3rd European PV-Hybrid and Mini-Grid Conference*, Aix-en-Provence, France, May 2006.

VII **S. G. J. Ehnberg**, E. Agneholm, G. Olsson, "Load Frequency Control of Renewable Energy Systems," submitted to *IEEE Transactions on Energy Conversion*.

VIII **S. G. J. Ehnberg**, E. Agneholm, G. Olsson, "Load Voltage Control of Renewable Energy Systems," submitted to *Renewable Energy*.

Chapter 2

Rural electrification in developing countries

Rural electrification is important to get people to stay in rural areas. The electrification is needed to secure the living standard and create opportunities for jobs. The urbanisation have to be limited to prevent the cities to grow too much.

Africa is a continent with a lot of problems and some of them can be solved by rural electrification. But it is not only in Africa the rural electrification has to be further developed. For rural electrification it is important to take local conditions into consideration to limit the costs. Examples of this is to use solar power in areas close to the equator and small scale hydro power where rivers are available.

2.1 Africa - a part of our world

Today over one billion people in Africa do not have access to enough energy. Energy resources do exist but usually the lack of suitable infrastructure limits the use of the existing resources. Most of the countries in Africa are developing countries and need to improve their energy infrastructure. Also the lack of appropriate technology to utilise the resources causes large problems, especially for the renewable sources [1].

There are several ways to provide energy to a society and electricity is one way. Electricity and especially electricity from renewables provide a sustainable solution to the problem. Other energy sources are often associated with a negative impact on the environment.

In different parts of Africa different solutions to the energy problems are required. In this chapter the focus is on rural areas but similarities can be found with areas that are isolated due to other reasons than geographical, such as political or economical.

The definition of a rural area have varied in the literature [2]. This diversity has had a large influence on the different rural electrification programs when it came to financial support and thereby the development of an area. Definitions have varied from single farms to provincial towns with up to 50 000 inhabitants. In this thesis the following definition has been used:

An area is considered rural when a grid extension is not economical and/or social possible in the near future.

2.2 Tanzania - a part of Africa

Africa is a large continent with many different countries having different prerequisites. Studies have been performed in Tanzania because it is a developing country. Furthermore it was possible to obtain weather data for the generation reliability studies. SIDA (Swedish International Development cooperation Agency) has been working in the country for many years and has thereby built up a large network of contacts. A lot of social and social/economical studies have been done in Tanzania [3, 4] which have been used as a starting-point in this study. During the project a study visit was made to the local electric company (TANESCO), the university of Dar-es-salaam and consultants working on-site.

Tanzania is one of the poorest countries in the world, with a BNP per capita of only 230 USD [3]. Tanzania is located on the east coast of Africa between Kenya in the north, Uganda in the east and Mozambique in the south. The population is 38.4 millions and the area is 943 000 km^2. Tanzania consists of the mainland, Tanganyika, and the islands Zanzibar, Pemba and Mafia. The official language is Swahili but English is the most common language in commerce and administration. English is also used in the later years of education. The centre of commerce is Dar-es-salaam but the capital is Dodoma. Tanzania is a democracy and the CCM (Chama Cha Mapinduzi) is the governing party and has been so since the liberation from the British.

In Tanzania only every fifth person has access to electricity and in the rural areas it is only every 20th person [2].

The electricity production is mainly based on natural gas turbines and hydro power. The gas turbines are located close to Dar-es-salaam and are mainly supplying the city that consumes around 70 % of the produced electricity in the country. The total installed capacity is around 900 MW. The main grid consists of a 220 kV line as a backbone that extends from Dodoma via Dar-es-salaam to Arusha, the second largest city in Tanzania. The availability of the power is very low and blackouts daily occur. Therefore backup systems are used for important loads or loads that are economically dependent on electricity, like hotels and restaurants. The backup systems are mainly powered by diesel generators.

A large problem, not only in Tanzania, is the non-technical losses. A study performed showed that up to 40 % of the delivered power was not charged for. There are two reasons for this. The most obvious reason is that the ability to pay is low. This problem has partially been solved by prepayment meters. The system works like a phone-card where you pay and get a number which is dialed into the meter. The other reason is theft, both intentional and unintentional. How large part of the theft that is unintentional is hard to estimate since many people play “stupid” if they are caught. In some cases it is clear that the owner does not know how electricity works and therefore the theft is often not very sophisticated and can easily be discovered.

Another problem is that a lot of equipment is stolen. For example, during the construction of an overhead line it had to be energised each night to prevent theft. Other things that often get stolen are transformer oil and support struts for metal towers.

During a field study in Dar-es-salaam the personal safety level was studied. The safety varied from high standard in hotels and official buildings to bare wires hanging between the walls in private homes. The awareness of the safety problem is very low. Wires both bare and covered hang 2-3 meters above ground but in some extreme cases even lower. During discussions with locals it became apparent that the interest and knowledge of personal safety were low.

When traveling through Tanzania the lack of interest of maintenance can easily be seen. Houses and especially transports are lacking maintenance. Pushing taxis and buses has do be done frequently. Trucks in poor condition were often seen along the roads. Not even spare tires were brought in the car and had to be purchased in case something happened. Repair shops are common and can be found almost anywhere.

During a study visit to a substation the lack of maintenance could easily be discovered. Some disconnecters had probably not been operated for tens of years and some did not work at all. Some of these problems may be due to economical reasons or lack of knowledge but it also shows a low general interest in maintaining equipment. People were found to be less stressed. In case something broke it had to be fixed and that was allowed to take time. According to discussions at TANESCO (the state owned electric company in Tanzania) the attitudes are about to change. Especially when young people that are working outside their village have to use transportation to go to work they are observant not to lose their jobs. This has lead to a great interest of maintaining their bicycles.

Developing standards are complicated and expensive. Therefore the standards in Tanzania have been adopted form the former colonial power, Great Britain. In many cases the British standards requires unnecessary high demands on components and operation. An example is the demand on transmission lines that have to be able to handle ice on the lines and heavy snow falls. This kind of standards make investments unnecessary expensive and do not allow local solutions to the problems [1].

2.3 Effects of rural electrification

There are several different effects of rural electrification, some positive and some negative.

- Environmental
  - Limit the contribution to the green house effect
  - Prevents deforestation
  - Limits pollution

  - Uses less of the worlds limited resources
- Economical
  - Stops the mitigation of poverty belts
  - Allows commercial and industrial activities
  - Causes an increased efficiency of agriculture
- Social
  - Allows more education
  - Allows entertainment
  - Improves safety and political stability
  - Allows medical treatment and supply of clean water
  - Creates more personal safety problems
  - Encourages more alcohol use
  - Allows longer working hours
  - Encourages prostitution
  - Causes bad influences of movies
  - Allows an increase of living standard

These items are some examples of various effects that can be expected as a result of electrification. Naturally the effects depend on local conditions and not all of the effects can be expected everywhere. In some cases there are other factors than lack of electricity that are limiting the development. It is not clear that all areas will benefit from electrification and therefore it is very important to study the local conditions before starting the electrification [5].

Electrification is a powerful tool for these effects but it should be remembered that in the majority of the cases electrification alone can not solve the existing economic or social problems.

2.3.1 Environmental effects

In many countries deforestation is a large problem as been discussed by [1, 4, 6]. The deforestation may lead to soil erosion and in the long run even deserts may be formed. The main problem is that wood is used for cooking. However, e.g. [2] discusses that deforestation will continue some time after the electrification since a new way of cooking has to be learned and used.

If the non-electrified areas in the world would increase their energy use utilising the same energy sources as today, the existing problem with the green house effect would become even worse. It would also increase the use of our limited natural resources [2, 6].

Electrification would affect both the indoor and outdoor pollution [4, 7]. The indoor climate would be better because of less smoke. The emissions outside would change, reduced if renewables are used, and more waste can be expected due to higher consumption.

2.3.2 Economical effects

The economical effect is probably the most obvious reason for rural electrification. It is well known that electricity is a catalyst for economic growth [1, 4, 2, 8, 9] and thereby in the standard of living.

Also the level of education will benefit of electrification [4, 2, 8, 10]. It can provide possibilities for adults to study after the working day when it is dark. It is much easier to read if electric light is used instead of candles. The possibilities to watch TV and listen to radio will make the people more aware of the world around them. The increased awareness will make it harder for people to get fooled by commercial or political powers. Also cooperations of farmers can be formed to meet the competition from large national and international companies.

By using water pumps for irrigation the efficiency of agricultural activities will increase [4, 2, 9]. This together with a higher educational level of the farmers will increase the efficiency even more.

By using electrical light there will be possibilities for commercial activities [1, 4, 2, 9, 10] in the evenings such as bars, restaurants and shops. By the use of light it is possible to extend the working hours.

2.3.3 Social effects

There are also large positive social effects of rural electrification. There will be possibilities for entertainments like TV, radio and music [1, 4, 2, 8, 9]. However, according to [4] movies may also have a bad influence on the people.

Electrification can also improve the medical situation. Many villages are located far away from a hospital. With a refrigerator vaccine and medicines can be stored locally which makes it possible for fast treatments even in rural areas. The need for fresh water is large in many areas and can be available by using electric water pumps [4, 2, 10].

It is important to make the living conditions good in rural areas as poor people otherwise will move to the urban areas to get a job. Since these people often have low or no education they have problems to get a job. Therefore they can not afford to live in the cities and consequently they will stay just outside the city where poverty belts are formed. [2, 10].

Public lighting is essential to make streets safer, especially for women. In [2] it has been found that electrification helps to create political stability through higher awareness of the people.

The light also means longer working hours and more stress, which may be harmful in the long run. More bars and restaurants will increase the intake of alcohol and have also lead to prostitution [4].

With electrification new dangers occur that may injure or kill people since knowledge of personal electric safety is low. Special equipment like batteries that contain acid may be another source of danger [6, 11].

2.4 Technologies for rural electrification

The most obvious way for rural electrification is an extension of the existing grid. Often it is too expensive but it gives high reliability as everywhere else. In [12, 13] a design method using Single Wire Earth Return (SWER) to limit the cost of a three phase installation is presented. SWER is an attractive design since it is a cheaper way to extend the grid. SWER is used in Australia and can supply loads up to 200 kVA that are distributed along a line that can be 300 km [14]. The SWER concept can also be used to connect distributed generation to the grid [15]. However, the effects on the wildlife of SWER are discussed which can make the use questionable.

When grid extension is not possible autonomous systems can be built. One way to supply such a system is to use diesel generators which have good generation reliability. Diesel generators have a low investment cost but the operational cost is high. In rural areas operational cost are even higher due to extra transportation costs for both fuel and spare parts. Diesel generators also contribute to the green house effect and use of our limited natural resources [6].

One way to limit the use of diesel fuel is to connect a renewable source to the system. There are different sources that are suitable to combine with diesel, such as solar [16], wind [17] or a hybrid system containing both solar and wind [18]. To limit the use even further a storage can be used as discussed in [19].

Building autonomous systems without diesel or other fossil fuels seems to be the most interesting scenario as discussed in section 2.3. There are several different sources that are of interest, like solar, wind, small scale hydropower and biomass.

The use of PV (Photo Voltaic) devices is discussed in [20] and it is shown that PV has a great potential for rural electrification, particularly for low power devices. According to [21] wind power is also an alternative for rural electrification but the stochastic behaviour of the wind is a problem. In areas where small rivers are available the use of small scale hydropower stations presents an option. In [9] the production of power from river flows or from a small dam are described to be the most useful sources. In [22] the use of biomass is suggested and discussed for rural electrification. However, the biomass fuel is not available everywhere [6] but at some places it can be a valuable source.

Another method of electrification is to use battery charging stations. At such places people can get their personal battery charged. A large problem is that the batteries have to be transported to the station. The transportation of the battery may have a negative effect on the lifetime of the battery [11]. Charging by solar power [23] or wind power [24] presents an alternative.

To avoid the battery transportation individual charging systems have been installed in each household, the so called Solar Home Systems (SHS) [25]. A SHS consists of a small solar panel, a battery charger and a battery. It is a low cost alternative and is already installed at several locations [6, 11].

Which method and source that is the best is hard to discuss in general terms. It is important to adopt the solution to the local conditions to get the maximum use of the available energy and the investments [7]. One of the most important factors when choosing power sources is the generation reliability which is further discussed in Chapter 3.

The control of the system should be dependent on the configuration of the power source components. In case of grid extension only the voltage has to be controlled locally which can be made in a variety of ways e.g. by tap-changers or reactive power compensation. For an autonomous system both the voltage and the frequency have to be controlled. If diesel generators are used the frequency control should focus on saving fuel while the voltage can be controlled by the excitation system of the generator. If a storage is applied it should be controlled so that its capacity is used up to its maximum. This in order to obtain as high availability as possible and still save fuel if a diesel generator is used. If wind is connected to the system it should be utilised to a maximum since the “fuel” is for free. If only renewables are used the sources should be used to a maximum not to waste any energy. The latter case is more discussed in Paper V, while the load control method is discussed in Chapter 5.

2.5 Autonomous system and commercial activities

Electricity by itself does not lead to economical development but it can be combined with some income generating activity. Autonomous systems have shown to be well suited for SMCEs (Small and MiCro Enterprises) [4, 7].

A SMCE is a small business where the activities to a large extent rely on the work of family members. It and can be both service and production enterprises. Service enterprises are businesses like bars, restaurants, guest houses, workshops and other support functions. Examples of production enterprises are pottery, weaving, dairy processing, local beer brewing, leather treatment, grain milling, small scale mining, bakeries, candle wax manufacturing, honey processing, welding, tinsmiths, soap making and battery charging [7].

The size of an autonomous system is dependent on the kind of commercial activity. In [7] it is shown that even systems of only a few tenth of kW are useful for commercial activities.

In [26] it is shown that Eco-design could be useful for SMCEs, not only from environmental aspects but also from economical aspects. The waste of resources can be limited for example by using less wood for carpentry or by changing to another non-traditional power source to limit the deforestation.

Even greater benefits can be made by connecting two or several villages. The availability of power and other power quality issues will increase as more production sources are included in the system. However, it would complicate the control of the systems and the distribution of the energy.

2.6 Prerequisites for rural electrification in a developing country

There are several important factors that have to be considered when building systems for rural electrification. This has been further discussed in [6].

The key factor, especially in developing countries, is to keep the system as available as possible to get social acceptance and make people trust the system. If a system can be trusted it will allow further investments related to electricity consumption. Therefore more robust designs are needed to minimise maintenance and the use of spare parts because transportation of spare parts is very time consuming and expensive. This can be achieved by using off-the-self products since they are often well tested and have a low-cost as compared to specially built equipment. If more than one system is built the systems should have the same standard to allow better prices when buying the components and possibilities to share the storage of spare parts. Furthermore, even installing over capacity of some equipment could be considered for reliability reasons. To get a robust design many things could be manually operated because of the low labour cost. The use of local operators would increase the control of the system and thereby the acceptance.

Training of the users of the system, not only operators and Engineers, is important to get the full benefits out of the systems as previously discussed. The training is also important to prevent injuries caused by electricity. The personal safety is particularly important due to the low awareness of the dangers of electricity.

New systems should be efficient and environmentally friendly to secure a sustainable future. During the design process of a power system it is important to take the total life cost into consideration and not only the installation cost. A low life time cost is very important due to the very limited purchase power but it should be remembered that the load situation may drastically change after an electrification [4]. A grid extension is in most cases not economically feasible.

A minimum of transports is required since it involves a great risk of damaging the equipment during the transportation due to the poor roads. It is also important to provide a power quality that does not break equipment. This is true also for low cost equipment. For example, even transportation of light bulbs are expensive. On the other hand there should be less requirements on non-destructive power quality issues in the system since most equipment is expected to be less sensitive for e.g. frequency deviations and voltage dips.

The electrification should be combined with some kind of income generating activity already in the design process to support both the economy and the acceptance among the people. It would be favourable if the system would be controlled by some kind of income generating activity to maximise the use of the system. A method for this is proposed in Chapter 5.

Chapter 3

Generation models for reliability studies

To be able to do reliability studies of isolated power systems models of the power sources of the system are needed. The generation models presented in this chapter are:

- Solar power model
- Wind power model
- Hydro power model
- Storage model

In this study the emphasis has been on modeling of solar and wind power because they are the technologies that most likely will be used in developing countries. For the other sources simpler models have been applied.

3.1 Solar power model

In this section a model for simulating six-minute mean values of global solar radiation without any geographical restrictions is proposed and discussed. The model is based on a Markov chain and uses only the geographical coordinates of the location and cloud coverage data as input. The model utilises the transitions between different levels of cloud coverage for hourly mean values which means that low quality data may be used. For the six-minute mean values another stochastically varying term is added.

3.1.1 Models of solar radiation

Several models have been proposed for global solar radiation. The random nature of global solar radiation is included in all proposal, whereas the way of implementing this in a model varies significantly. In [27, 28, 29] the daily global solar radiation is modeled (thus the yearly variations). However, for photovoltaic power generation in an autonomous electric power system [30] a higher time resolution of the simulation is needed. Such a model would be applicable in a system with a storage capability that is higher than the daily load demand. The models in [27, 29] require several years of solar radiation measurements which for most locations in developing countries are not available. The model proposed by [28] is adapted for clear sky conditions but the authors mention the importance of the cloud coverage. In [31] the hourly radiation has been modeled but the model can be difficult to apply due to data requirements. Monthly average values of global radiation are needed which only can be obtained from long time measurements. In [32] another model is proposed but the problem with input data remains. A location-dependent factor is used in [32] which is dependent on the distribution of the solar radiation. This model can only be used when a large amount of solar radiation data is available.

Outside the atmosphere the solar radiation can be accurately determined [33] whereas the atmosphere will induce the randomness [31]. The transmittivity of solar radiation in the atmosphere depends on various factors, e.g. humidity, air pressure and cloud type. A factor that has a great impact, maybe the main factor [34], on the transmissivity is the cloud coverage [28, 35]. By assuming a deterministic relation between cloud coverage and hourly global solar radiation the need for measurement of the latter disappears. Cloud observations can be used because of the simplicity of measuring. No expensive equipment is needed. The level of cloudiness is often expressed in Oktas which describes how many eighth parts of the sky that are covered with clouds [36]. Another method of describing the atmosphere is by using the clearness index. The index was proposed already in 1924 by Angström [34] and is further developed by [34, 37]. The index can be used to determine the distribution of the radiation but not the expected variations during a day. The changes during a day are very important when designing power systems. However, in [38] it is shown that the index can be combined with Markov transition matrices and thereby the changes during a day can be studied. The method can also be used to model the solar radiation at locations where no measurements have been conducted. On the other hand it requires measurements from neighbouring locations.

The solar radiation distribution is expected to be similar in areas with similar climatological conditions [32]. This means that the method can be used when cloud observations are available for an area with similar climatological conditions. In reliability simulations for power systems without storage capacity, simulation data with higher resolution than one hour are in some cases needed. This is the case when short-duration interruptions are of interest.

In this study a model which is a combination of a solar radiation model dependent on the cloud coverage (deterministic) combined with a simulation model of cloud coverage (stochastic) is proposed. More about the model including a validation of data from Göteborg can be found in Paper I.

3.1.2 Extraterrestrial and meteorological relationships

The radiation outside the atmosphere is dependent of the earth rotation around the sun, around its own axis and the tilt of the earth. The elevation angle is the angle of the sun above the horizon and can be described by Eq. 3.1 - 3.2 [33].

The equation for seasonal effects, Eq. 3.1, is an approximation under the assumption of a circular orbit of the earth around the sun. This assumption is allowed because the excentricity is only 0.07. Eq. 3.2 describes the daily effects and their dependence on the geographical location.

$$\delta_s \approx \Phi_r \cos\left[\frac{C(d-d_r)}{d_y}\right] \tag{3.1}$$

$$\sin\psi = \sin\phi\sin\delta_s - \cos\phi\cos\delta_s\cos\left(\frac{C\cdot t_{UTC}}{t_d} - \lambda_e\right) \tag{3.2}$$

where:

δ_s	Solar declination angle, the angle between sun and the plane of the equator [rad]
Φ_r	The tilt of the earth‘s axis relative the orbital plane of the earth around the sun, $\Phi_r = 0.409$ [rad]
C	Constant, $C = 2\pi$ [rad]
d	Day of the year [days]
d_r	The day of the year at summer solstice, 173 (22 June) for non-leap years [days]
d_y	Total number of days in one year [days]
ϕ	Latitude of the location [rad]
λ_e	Longitude of the location [rad]
ψ	Elevation angle [rad]
t_{UTC}	Time according to the Coordinated Universal Time [h]
t_d	Time of the day [h]

Eq. 3.2 does not include a conversion to local time from the Coordinated Universal Time (UTC). A conversion is needed for the reliability calculations since the loads often have a high correlation with local time.

The effect of the clouds in the simulation model for global solar radiation adds randomness to the model. The importance of the randomness in the atmosphere is also discussed in [31]. An empirically determined relationship between the global solar radiation, the elevation angle and the cloud coverage, Eq. 3.3, was obtained by the authors of [35]. The relationship was derived after many years of cloud observations, solar elevation measurements and global solar radiation measurements. The relationship is:

$$S = \left[\frac{a_0(N) + a_1(N)\sin\psi + a_3(N)\sin^3\psi - L(N)}{a(N)}\right] \tag{3.3}$$

where S is the global solar radiation and N is the number of Oktas; the values of the constants $L(N), a(N)$ and a_i for $i = 0, 1, 3$ are given in Table 3.1.

Table 3.1: The empirically determined coefficients for Eq. 3.3 [35].

N	a_0	a_1	a_3	a	L
0	-112.6	653.2	174.0	0.73	-95.0
1	-112.6	686.5	120.9	0.72	-89.2
2	-107.3	650.2	127.1	0.72	-78.2
3	-97.8	608.3	110.6	0.72	-67.4
4	-85.1	552.0	106.3	0.72	-57.1
5	-77.1	511.5	58.5	0.70	-45.7
6	-71.2	495.4	-37.9	0.70	-33.2
7	-31.8	287.5	94.0	0.69	-16.5
8	-13.7	154.2	64.9	0.69	-4.3

By examining global solar radiation measurements it can be seen that the radiation varies within a one-hour period. This phenomenon can be simulated by introducing a statistically varying term according to equation 3.4. This stochastic variable (ε) is proposed to have the same distribution as the short duration variations seen in the measurements.

$$S_{stat} = S + \varepsilon \tag{3.4}$$

where S_{stat} is the solar radiation with time steps smaller than one hour. The stochastic variable (ε) can be estimated through cross validation, the so-called “hold out method” [39]. The deviation from the hourly mean values during day time can be fitted to a normal distribution where the mean value and the standard deviation can be estimated.

3.1.3 Cloud coverage simulation

Cloud coverage data are not available everywhere. At some locations only short series of measurements are performed or the data are of low quality and therefore a simulation model is needed. A Markov model is proposed to generate cloud coverage data from which global solar radiation can be obtained. A Markov model is suitable as a structure to describe the stochastic variations and dependencies. The states in the model represent the number of Oktas and the transition probabilities were obtained from measured values in an intuitive way:

$$\hat{\lambda}_{ij} = \frac{f_{ij}}{\Sigma_{k=0}^{8} f_{ik}} \tag{3.5}$$

where:

$\hat{\lambda}_{ij}$	is the estimated transitions probability
f_{ij}	is the number of transitions from cloud coverage level i to level j
f_{ik}	is the number of transitions from cloud coverage level i to level k

The seasonal variations of the transition probabilities were in some studies found to be large and therefore more than one transition matrix were needed. This is further discussed in Paper III.

3.2 Wind power model

In this section a model is proposed for generating simulated power output time series from a wind turbine. The model is suitable for locations with low quality data or with limited data. The model is based on a state-space model (Markov), "the power law " [40] and data from a conventional wind turbine [41]. The transition probabilities in the state-space are determined by using wind speed measurements. The model can be adapted to different geographic areas by using the yearly mean wind speed of the desired location.

3.2.1 Other wind speed models

Many research projects have focused on wind speed modelling. The methods of the modelling may be quite different but all of them include some statistical description of the variations. The models are also calibrated using field measurements as a basis of the simulations. The need for statistical wind power models is discussed in [42]. There are two main reasons for wind speed modelling; one is to make a forecast and the other is to calculate the expected mean values and variations. Short time forecasts can be performed whereas it is much more difficult to perform forecasts on a long time basis [43]. For operational purposes forecasts are needed for determining the power from wind turbines. Forecasts can also be used for warning systems such as predicting gusts which affect the operation of wind turbines [44].

Long term studies are needed in order to provide better long term predictions. It is well known that the wind speed distribution can be fitted to a Rayleigh distribution or the more general Weibull distribution [42, 45, 46, 47, 48, 49]. Long time series of good quality measured data are needed to parameterise the models. Many of the models are rather complicated and therefore they need large computational resources. This is not practical when the simulation of the wind speed distribution is only a small part of the total system simulation.

When models are used they can often be simplified by limiting their operating range to a certain region; for example for estimations of the power output of a wind turbine [50]. Some models are adapted to wind farms [51, 46] and need to be more complex than models for individual turbines. The wind direction is of great importance because of the shading effects on other wind turbines in the farm. For simulation of single wind turbines the shading effect can normally be neglected.

In [52, 53] Markov models are used to simulate wind speed series. One great advantage of using a Markov model is that the behaviour is based only on current data, while historical data are condensed in the state. In [52] Markov models are coupled to the simulation of wind direction. A combination of simulating wind speed and wind direction is very useful because normally there is a strong correlation between the speed and direction of the wind. Coupled models are especially important for areas having great variations in the topology [54]. Typical examples are coastal areas where it can be beneficial to install wind turbines. Normally there are great differences between land and sea wind. To determine the parameters of the model measurements of both wind speed and wind direction are needed. If only one single Markov chain is included in the model the wind speed intervals have to be larger than if two or more chains are used. This in order to get a manageable number of elements.

In [53] the authors have proposed two different models which both are based on the Markov theory. The first model is a Markov model with 19 states. The transition probabilities were calculated using measured wind speed data. This method had only correlation between two consecutive values. In the second model the wind speed is divided into three regions, weak (states 1-7), medium (states 4-12) and strong (states 11-19). Overlapping is allowed to enable single high/low values in one region. A start region and the time spent in each region are determined using the originally measured data. The duration of the wind speed in each group of states is varied stochastically. On average the wind speed is one third of the time in the weak-wind region, half the time in the medium-wind region and $1/6$ of the time in the strong-wind region. The simulation time step is one hour. According to the authors a further split into three seasons, winter (120 days), midseason (77 days) and summer (168 days) is needed.

3.2.2 The state-space model

The wind speed data has to be discretised to fit into the proposed two Markov chains model. One chain is applied for hourly mean values that are below the yearly mean and the other chain is used for values above the yearly mean value. This model split is done to better describe the two level behaviour that can be seen in measurements. A random transfer between these two levels of the wind measurements can also be seen. This wind behaviour may be explained from the fact that the wind comes from different directions.

To make the simulation more adaptable for wind speed generation data the yearly mean value was normalised to one. This can be done without changing the distribution of the wind speed and the dependencies between the two following wind speeds. By normalising the wind speed data the data could easily be adapted to any location. By scaling it with the yearly mean wind speed value the distribution of the wind speed series will be kept.

By using measured wind speed data as an input for the model it is possible to determine the transition probability matrices for the Markov chains. The two models are defined as if the last hourly mean value was above or below the yearly mean value. In the low wind Markov chain it is occasionally necessary to model some high values to model high wind squalls. Low wind squalls also exist in the high wind and therefore the high wind model must take this into account. The low wind model was discretised into 9 levels whereas for the high wind model 14 levels were used. The larger number of levels for the high wind model is due to a larger span of wind speeds. In Table 3.2 the wind speed intervals are presented.

Table 3.2: The discretisation of the wind speed data for the Markov models.

Level	Low wind interval $[m/s]$	High wind interval $[m/s]$
1	< 0.1	< 0.7
2	0.1-0.3	0.7-0.9
3	0.3-0.5	0.9-1.1
4	0.5-0.7	1.1-1.3
5	0.7-0.9	1.3-1.5
6	0.9-1.1	1.5-1.7
7	1.1-1.35	1.7-1.9
8	1.35-1.7	1.9-2.1
9	> 1.75	2.1-2.3
10		2.3-2.5
11		2.5-2.7
12		2.7-2.9
13		2.9-3.25
14		> 3.25

The transition matrices can be estimated in many ways whereas the most intuitive one is:

$$\hat{\lambda}_{ij} = \frac{f_{ij}}{\Sigma_{k=1}^{n} f_{ik}} \tag{3.6}$$

where $\hat{\lambda}_{ij}$ is the transition probability from state i to state j; f_{ij} is the number of transitions from state i to state j in the input data set and n is the number of states in each model.

The mean value for each level in the model has to be chosen in order to not change the mean value of the wind speed and thereby increase the discretisation errors. The mean value has to be determined from the original measured wind speed data. Ten simulations with the normalised model were performed and the total mean value of each simulation is shown in Figure 3.1.

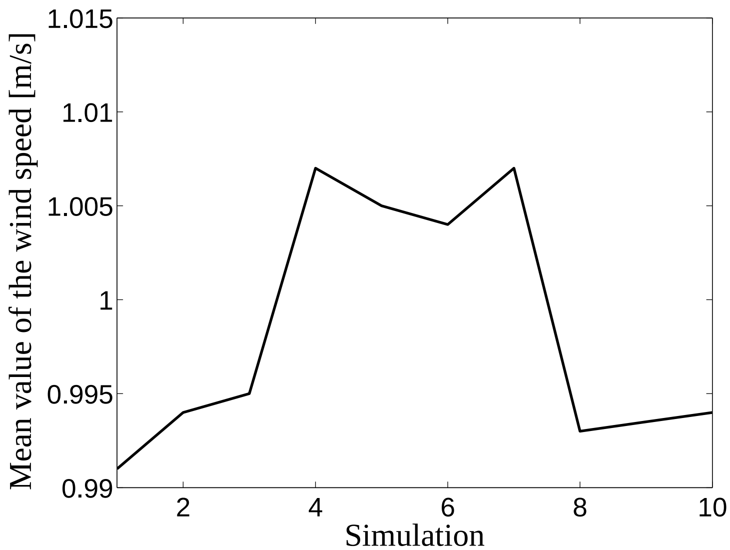

Figure 3.1: Mean value of ten wind speed simulations using wind speed data from Göteborg.

Location specifics could be included in the model by its yearly mean value since the model is normalised according to the yearly mean value. If the simulated wind speed data is multiplied with the yearly mean value of the desired location artificial wind speed data can be obtained. The data has the same distribution as the input data but with the local yearly mean value. More about this model can be found in Paper II.

3.2.3 Wind speed variations with altitude

It is a well known fact that the wind speed varies with the altitude. Wind speed measurements at many altitudes are in most cases unpractical, especially in developing countries. Additionally it is seldom known which altitude that is of interest at the time of the measurements.

By using a relationship between different altitudes only a measurement at a reference level is needed. One commonly used relationship is “the power law” [40] or “Justus formula” [55] as can be found in Eq. 3.7.

$$\frac{v(z_2)}{v(z_1)} = \left(\frac{z_2}{z_1}\right)^{\alpha} \tag{3.7}$$

where z_1 is the altitude of the measurement and z_2 is the altitude where the wind speed estimation is desired. $v(z_1)$ and $v(z_2)$ are wind speeds at height z_1 and z_2, respectively. α is the wind profile constant and is dependent on various factors e.g. altitude, wind speed, time of the day, season of the year, nature on the terrain and temperature. In [40] the authors have proposed a relationship according to Eq. 3.8, to determine α. This relationship has been used in this study.

$$\alpha = a - b \cdot log_{10} v(z_1) \tag{3.8}$$

During day time typical values for a and b are 0.11 and 0.06, respectively whereas 0.38 and 0.209 are typical values during night time.

3.2.4 Wind turbine

Today there are wind turbines in a wide range of sizes from less than 10 kW up to several MW. The design of small wind turbines differs much from that of large turbines. Small turbines are mostly based on direct-driven machines with permanent magnets. The aerodynamic profiles also differ and since manufacturers of wind turbines have less interest in small turbines the wing-profile is less developed as compared to large turbines.

In this study the wind turbines use the wind speed as input data. This is achieved by using the so-called wind-power curve of a wind turbine. The wind-power curve is the relation between the wind speed (v) and the power output (P) of the wind turbine and differs for different types of wind turbines. The wind-power curve used in this study is for a typical wind turbine. To describe the wind-power curve Eq. 3.9 was fitted, using the least-square method, to the data given by a manufacturer [41]. The output power (P) data was normalised, the nominal power (P_n) is equal to one, to be more generally applicable.

$$P = \begin{cases} 0, & v < u_c \\ Av^5 + Bv^4 + Cv^3 + Dv^2 + Ev + F, & u_c \leq v \leq u_p \\ 0, & v > u_p \end{cases} \tag{3.9}$$

The coefficients in equation 3.9 were estimated to: A=$-2.0763 \cdot 10^{-6}$, B=$2.0046 \cdot 10^{-4}$, C=$-7.0343 \cdot 10^{-3}$, D=0.1067, E=-0.5965 and F=1.0963.

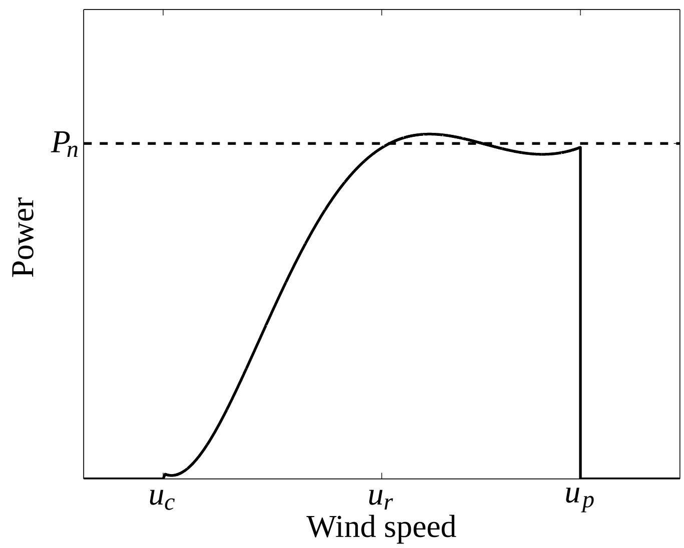

Figure 3.2: Wind-power curve of a down scaled wind turbine.

The cut-in wind speed u_c is the minimal wind speed needed for the wind turbine to generate power and is normally set to 4 m/s. If the wind speed is less than u_c there is not enough power in the wind to overcome the friction and other losses in the wind turbine. The wind speed for nominal power output, u_r, is a design parameter and is normally chosen to 15 m/s. If the wind speed exceeds a certain value, u_p, the wind turbine has to be shut down to protect the turbine. The protection wind speed is typically dimensioned for 25 m/s. The wind speeds u_c, u_r and u_p are all dependent on the wind turbine construction.

3.3 Hydro power model

Another interesting power source is small scale hydro power, so-called micro turbines. During the last few years the interest for them has increased and since the hydro power can be used and built also for small flows they are of interest in the type of studies performed in this thesis. The model used in this study is a constant flow-of-river with a small reservoir. The reservoir could supply the maximum load, see section 4.1.1, during not more than an hour.

The mean power from the flow of river (P_{hydro}) was calculated according to Eq. 3.10. In all other aspects the hydro power model was considered ideal.

$$P_{hydro} = \eta_{hydro} \frac{\rho_{water} V g h}{3.6 \cdot 10^6 \cdot t} \tag{3.10}$$

where η_{hydro} is the efficiency of the complete system, ρ_{water} is the density of water (approx. 1000 kg/m^3), V is the volume of the water per hour, g is the gravity constant (approx. 9.80 m/s^2), t is the time and h is the height of the water.

3.4 Storage model

Currently there are several different storage technologies available. The main types are mechanical (flywheel, pumped hydro etc.), electrical (SMES, capacitors etc.) and electrochemical (batteries etc.) [56]. Which storage technology to use can vary because the applicability of each technology mostly depends on the location. Currently some of the technologies are not sufficiently mature for this application but might be in the future. Therefore the behaviour of the storage has been considered ideal in aspects such as efficiency and discharge depth during this study.

Chapter 4

Generation reliability

In order to run a power system safely it is necessary to perform reliability calculations. For example reliability studies are needed for design and scheduling of maintenance. This is the subject of several books e.g. [57].

Reliability analysis is often divided into the three power system levels: generation, transmission and distribution. Each of these levels has its own character and thereby its own problems. The division into the three levels is suitable for large power systems where all three levels are needed but in some systems only some of the levels are required [58], like small systems.

The most important reliability aspects is the generation reliability but it has low impact on the total loss of power for costumers in large power systems [58]. This since the redundancy is normally high among the different production sources. However, in a system with a low number of production sources or sources with low availability the generation reliability is the most important factor.

In generation reliability parameters like LOLP (Loss of Load Probability) and LOLE (Lost of Load Expectancy) are often used [57]. LOLP is the probability/risk that the annual peak load exceeds the generation capacity. This parameter gives the probability that the maximum load cannot be supplied. LOLE gives how much load that is expected not to be supplied.

In this study the terms availability and unavailability are used. Availability can be seen as the probability that the load at an arbitrary time is covered by production or storage. Unavailability is one minus the availability. Unavailability is close to LOLP but the annual peak load is not considered. Instead the load requirement, see Section 4.1.1, is considered. Other key parameters than the availability are also studied, like LOLE for the hourly loads and the distribution during the day of the lost load. The latter is especially interesting to study in systems based on renewables where the time of the day is important.

There are two main ways to study generation reliability: analytic and by using simulations. Different mathematical techniques for analytic determination of the availability of different stochastic power sources are used in [59]. To be able to use such a method all models used in the study have to be described by stochastic variables. Usually it is difficult to introduce deterministic relationships.

Another common method for reliability analysis is to use Monte Carlo simulations [60, 61]. Monte Carlo is especially useful for complex systems with a lot of dependencies. In addition Monte Carlo simulations can handle deterministic models. Monte Carlo simulations are quite computer extensive but today this is not a large problem. The main idea with the Monte Carlo simulations is to simulate several typical situations. The accuracy is dependent on the number of simulations and the behaviour of the stochastic models in the typical simulation [62].

The main reasons for reliability analysis of a small power systems is to properly design the generation capacity. Normally the analysis is used for comparing different sources or a combination of sources. Economical factors are often considered as the main factors. Reliability analyses have been performed for different energy sources like solar [63], wind [64] and hybrid systems [65, 66]. Also the need of storage is important as discussed in [67]. The analysis can also be used to test different control strategies. There are different reasons for this but the most common one is to limit the use of diesel generators [68].

In this study the focus is on finding what can be achieved by combining different renewable energy sources. This study is not complemented with an economical study since the conditions are different in different parts of the world. The cost is also dependent on which kind of loads that need to be supplied. The loads are often geographically dependent or dependent on other factors than the design of the power system. Typical examples are political reasons and national borders.

4.1 Models and input data

It is not only the generation models presented in Chapter 3 that affect the result of the simulations. The load models are especially important as well as the model of the power flow and the input data. The input data are both meteorological data and the geographical location (needed for the solar model).

4.1.1 Load model

For reliability studies the loads play an important role since they determine what should be achieved. In industrialised countries the total load curve is a combination of domestic, industrial and commercial loads and both systems and loads are more or less fixed. In rural power systems in developing countries the load situation is completely different. In the existing situation there is no or extremely little electrical load. The real load curve is therefore much more uncertain and can be expected to include greater variations than in industrial countries. Industry activities can be planned after the access of power. Since one of the generation sources is the sun, high loads are desired during hours with sun (daytime). However, it is unreasonable for the load to adapt to every variation in the generation and therefore some control must be included.

Load models are well studied [69, 70]. Special attention has been made on models for developing countries. The load situation in rural areas, which is the focus in this thesis, differs from the situation in urban areas and therefore loads in rural areas need to be focused on [71]. There are two main load models, one which models the complete load as a varying load [72] and one that is based on connection and disconnection of individual loads[7, 73].

The load curve in this study, see Figure 4.1, should be seen more like a “power requirement”, because it is hard to predict the actual load behaviour. It is perhaps more important for industrial activities to know what can be expected for the system then the actual behaviour. That can then be used for planing purposes.

A load curve was selected to represent both daytime load (mainly industry) and lower night time load (education and leisure activities). The maximum load occurs between 7.00 am and 7.00 pm. During night time the demand is only ten percent of the maximum. The peak day time load consists of not only the demand from industrial activities but also of other smaller loads like schools for the young children . At night time the demand may come from schools for education of older children and adults and for power for equipment that has to operate more or less continuously, like refrigerators.

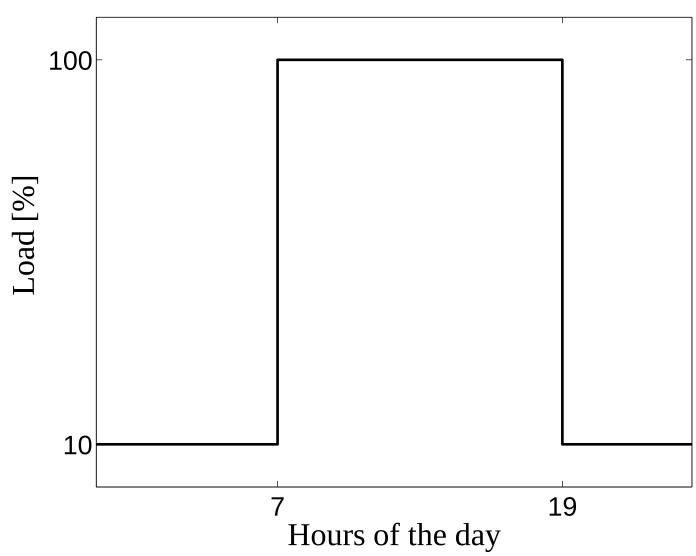

Figure 4.1: The load curve used for reliability studies.

4.1.2 Power flow model

In this study the model of the power flow can be seen in Figure 4.2. The power of the solar and wind will be absorbed directly by the system while the power from the hydro power usually comes via some reservoir. The storage can both absorb and deliver energy to the system. Some power is lost in the conversion to and from the storage and is denoted as an efficiency of the load. In the figure the the following notations are used: P_{wind} is the wind power, P_{solar} is the power from the sun, P_{hydro} is the water power supplying the reservoir, P_{load} is the load of the system, P_{losses} is the losses in the storage, W_{hydro} is the available energy in the reservoir and $W_{storage}$ is the available energy in the storage.

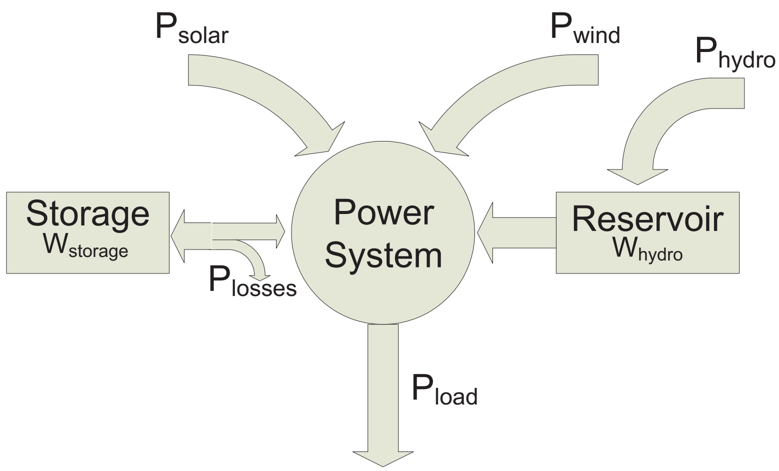

Figure 4.2: Model of active power in the system. The power from solar and wind goes directly to the system while the hydro power enters the system via a reservoir. The storage may both absorb and deliver energy but has some losses.

The power system is considered ideal in the sense that the system has no losses, the reliability is 100 % and the system require no maintenance.

4.1.3 Meteorological data used

In order to provide input data for the stochastic models of wind and solar power meteorological data are needed. Since the project was limited in time, already collected data has been used. Data was collected both from Sweden and Tanzania. The data available from Tanzania was of low quality , which is discussed further in Paper V, but the data could still be used in the simulations due to the choice of the model structure. However, for comparison studies data from Sweden, having much higher quality, has been used.

4.1.4 Geographical location

As input in the stochastic models of wind and solar power weather data are needed to train the models. In the solar power model the geographical location is also required. The location used in the comparison study in this chapter was Mbeya ($8.9\,^{\circ}$S, $33.5\,^{\circ}$E) located in the southern Tanzania. Mbeya was chosen despite it is a small city. This since weather data was hard to obtain for rural areas. The data from Mbeya was of low quality is discussed in Paper V. However, the data showed a similar behaviour as for Dar-es-salaam, where better data were available, as also described in the paper.

4.2 Simulations

The studies have been performed by using Monte Carlo simulations. All the generation models presented in Chapter 3 and load models in 4.1.1 are used in the power flow model in 4.1.2. The simulations have been executed with a time step of one hour.

The starting values of the models are randomly chosen to not affect the result of the simulations. Both the storage and the reservoir are considered empty. In the simulations the load is considered supplied if the condition in Eq. 4.1 is fulfilled.

$$P_{load} \cdot t_{step} \leq P_{wind} \cdot t_{step} + P_{solar} \cdot t_{step} + W_{storage} + W_{hydro} \tag{4.1}$$

where the nomenclature has been explained in Figure 4.2. The energy level storage and the reservoir are then updated before the next simulation step, Eq. 4.2 for the storage and Eq. 4.3 for the reservoir.

$$\text{if } P_{load} \cdot t_{step} > P_{wind} \cdot t_{step} + P_{solar} \cdot t_{step} + W_{storage}(i)$$

$$W_{storage}(i+1) = 0 \tag{4.2a}$$

otherwise

$$W_{storage}(i+1) = W_{storage}(i) + P_{change} \cdot t_{step} - P_{losses} \cdot t_{step} \tag{4.2b}$$

However, $W_{storage}$ has limitations

$$0 \leq W_{storage}(i+1) \leq W_{storage}^{max} \tag{4.2c}$$

The update of the storage is that if the load is larger than the energy produced by the sources and the storage the storage will be considered empty for the next simulation step. If the load is less than the available energy the surplus, except the losses, will be added to the storage. However, the storage may never exceed the capacity of the storage $W_{storage}^{max}$.

$$\text{if } P_{load} \cdot t_{step} < P_{wind} \cdot t_{step} + P_{solar} \cdot t_{step} + W_{storage}(i)$$
$$W_{hydro}(i+1) = W_{hydro}(i) + P_{hydro} \cdot t_{step} \quad (4.3a)$$
$$\text{but } W_{hydro}(i+1) \ngtr W_{hydro}^{max}$$
$$\text{if } P_{load} \cdot t_{step} > P_{wind} \cdot t_{step} + P_{solar} \cdot t_{step} + W_{storage}(i) + W_{hydro}(i)$$
$$W_{hydro}(i+1) = P_{hydro} \cdot t_{step} \quad (4.3b)$$
$$\text{otherwise}$$
$$W_{hydro}(i+1) = W_{hydro}(i)$$
$$+P_{hydro} \cdot t_{step} + P_{change} \cdot t_{step} + W_{storage}(i) \quad (4.3c)$$

If the load is less than the available energy from the wind, solar and in the storage the energy from the hydro will be added to the reservoir for the next simulations step. However, the reservoir may never exceed the capacity of the reservoir, W_{hydro}^{max}. In case the load is not fulfilled the reservoir will only contain the energy from the hydro for the next simulation step. When not all energy available in the reservoir is used the reservoir will be emptied by the energy needed and filled with the energy of the hydro power.

P_{change} is the change in power when not considering the storages and can be found in Eq. 4.4. P_{losses} is the losses in the storage and is defined in Eq. 4.5.

$$P_{change} = P_{wind} + P_{solar} - P_{load} \quad (4.4)$$

$$P_{losses} = \eta_{storage} \cdot P_{change} \quad (4.5)$$

In Eqs. 4.2-4.5 it can be seen that the storage is first used and then the volume of the reservoir is used. The reason for this is that the storage can be refilled by both the wind and solar power which are larger than the small river flow.

Since the focus in this study is on the methods and relations between the different sources the relative size of each source is of more interest. Therefore the Maximum Generation Capacity (MGC) has been used for the sources. MGC is the ratio of the rated (solar peak power) power and the maximum load. For storage the Maximum Storage Capacity (MSC) is used, which is the ratio between the capacity of the storage and the maximum load. MGC and MSC are combined with subscripts that are explained in Table 4.1.

Table 4.1: Explanation of MGC and MSC for different sources and storages.

MGC_{wind}	The ratio between the rated power of the wind turbine and maximum load.
MGC_{solar}	The ratio between the peak power of the solar power (clear sky and the sun in zenith) and the maximum load.
MGC_{water}	The ratio between the power generated by flow-of-river and maximum load.
$MSC_{storage}$	The ratio between storage capacity and maximum load.
$MSC_{reservoir}$	The ratio between maximum energy to be stored in the reservoir and maximum load.

To be able to investigate the behaviour of an individual production source or a combination of sources and storage not all sources or storages are used in all simulations. Not all possible combinations are investigated since the combination of solar and/or wind is planned to be the main sources and the other combinations are of less interest. The studied combinations are:

- Solar power
- Solar power with storage
- Solar power and hydro power
- Solar power, hydro power and storage
- Wind power
- Wind power and storage
- Solar power and wind power
- Solar power, wind power and storage
- Wind power and hydro power
- Wind power, hydro power and storage
- Solar power, wind power and hydro power
- Solar power, wind power, hydro power and storage

As previously described the basis of a Monte-Carlo simulation consists of repeated simulations. In this study only one simulation was performed for each data point because, as shown in Figure 4.3, little useful information will be achieved by repeating the simulation.

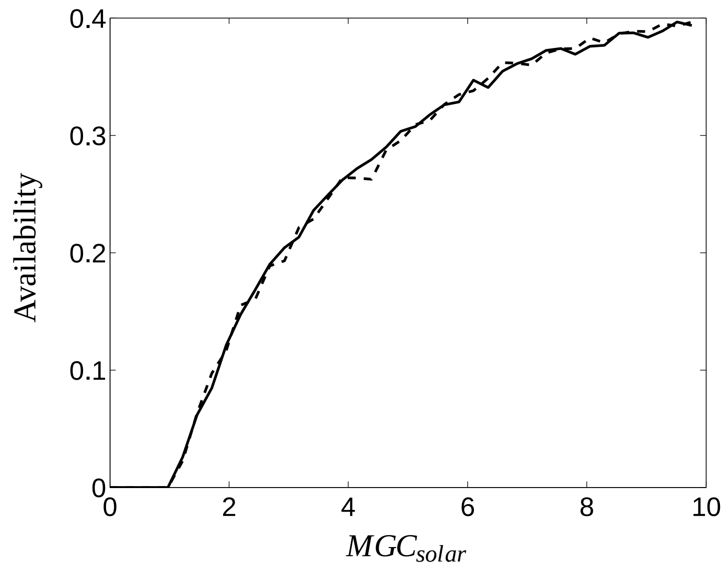

Figure 4.3: Availability of a power system with only solar power generation where the solid line indicates the mean value of ten simulations while the dashed line shows the result from a single simulation.

There is a strong resemblance between a single simulation and the mean value of ten simulations because the Markov chains are ergodic [74]. Since they are ergodic it reaches the same stationary solution, independent of the initial conditions. Each single simulation is long enough to converge into a stationary solution. Since the chains are ergodic the initial state is not important. By using only one simulation per data point the computational time will be significantly reduced.

For the reliability calculations in this chapter a time step of one hour is used despite the fact that the stochastic varying models, presented in previous chapter, have been developed for shorter time steps. From Figure 4.4 it can be concluded that there is a little need of smaller time steps than one hour in this type of calculations. Figure 4.4 shows the case of only solar power and load. The differences seen in the figure are not greater than the difference between two separate simulations. A difference should not occur because the mean value is independent on the length of the time steps. In some cases the use of a smaller time step is necessary, like calculations of the number of times that a shortage occurs and the duration of the shortages. In this thesis these kind of calculations are performed with a time step of one hour. These studies are just an estimation of different system configurations. To be able to compare different configurations shorter time steps are not necessary at this stage. Especially when using storage or hydro power, the short-term fluctuations in solar and wind will be smoothed out.

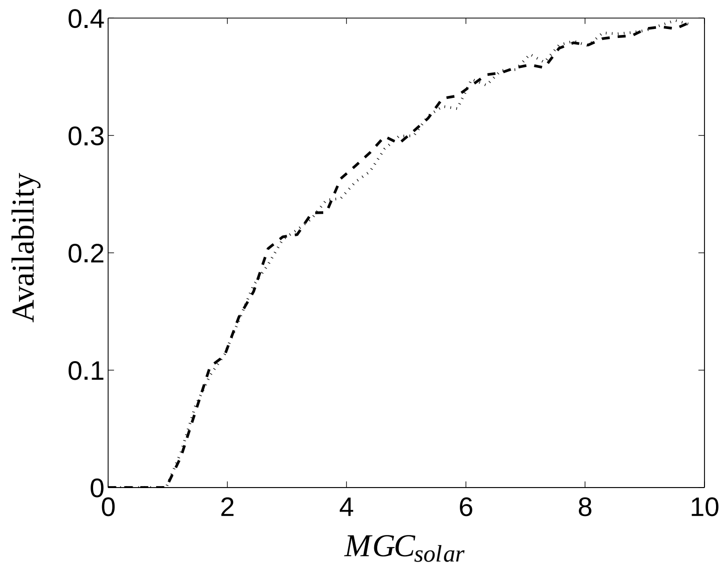

Figure 4.4: A comparison between availability calculations of solar power with different time steps, one hour (dashed line) and 6 minutes (dotted line).

4.3 Results

Results from the studies are presented in Table 4.2. More detailed results determined with the same method for studying wind power can be found in Paper II, for solar power in Paper III and for various combinations of energy sources in Paper IV.

In all presented cases in Table 4.2 the total MGC is around 10 which was the limit when nothing more could be gained by increasing the capacity which can be seen in Figures 4.3 and 4.4. The limit is inside the range proposed by [55] as an optimal size for autonomous wind energy systems.

It is not only the overall availability that is of interest. During day time there are large risks for power shortages. This information can be useful for better planning. In Figure 4.5 an estimation of the number of hours during the day when the load is not supplied can be seen. The squares denote a solar powered system while the stars denote a wind powered system. For the solar powered system there is no energy available during the night. The wind energy is more or less constant during the day and the behaviour seen in the figure is due to the load that is much higher during daytime. This is further discussed in Paper IV.

Table 4.2: The availability for different configurations for the system shown in Figure 4.2 with the use of Eq. 4.1-4.4.

Case No.	*MGC* Solar	*MGC* Wind	*MGC* Hydro	*MSC* Storage	*MSC* Reservoir	Total MGC	Total MSC	Availability
1	10	0	0	0	0	10	0	0.43
2	0	10	0	0	0	10	0	0.87
3	10	0	0	1	0	10	1	0.76
4	10	0	0	3	0	10	3	0.99
5	0	10	0	1	0	10	1	0.94
6	0	10	0	3	0	10	3	0.98
7	10	0	0.05	0	1	10.05	1	0.73
8	10	0	0.1	0	1	10.1	1	0.98
9	10	0	0.2	0	1	10.2	1	0.99
10	0	10	0.05	0	1	10.05	1	0.93
11	0	10	0.1	0	1	10.1	1	0.95
12	0	10	0.2	0	1	10.2	1	0.96
13	10	0	0.1	1	1	10.1	2	0.99
14	0	10	0.1	1	1	10.1	2	0.97
15	5	5	0	0	0	10	0	0.92
16	5	5	0	1	0	10	1	0.99
17	5	5	0.1	0	1	10.1	1	0.99
18	5	5	0.1	1	1	10.1	2	0.99
19	5	5	0.1	3	1	10.1	4	0.99

When storage is introduced in the system the number of incidents with lacking power that will occur during a certain hour of the day will change. The numbers will drop and they drop more in the mornings and less in the evenings as demonstrated in Figure 4.6. The reason for this is that the storage is filled up during the night and then used during the day.

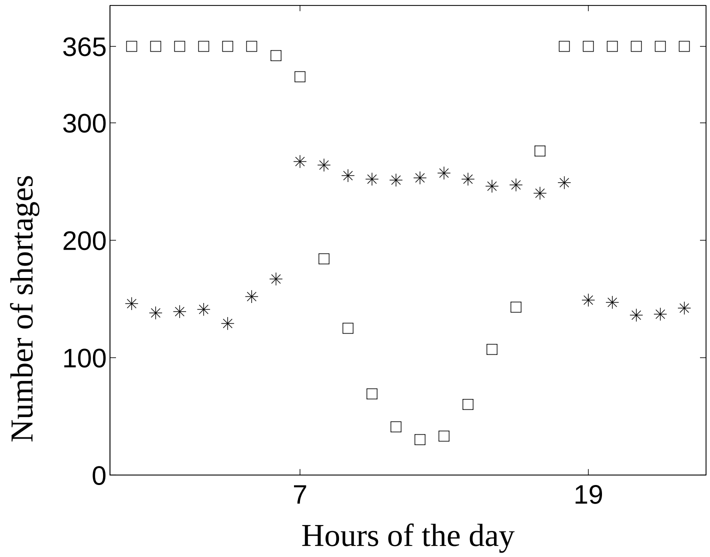

Figure 4.5: The number of shortages per year for each hour of the day. The squares refer to a solar powered system while the stars refer to a wind powered system. The *MGC* is the same for both the cases.

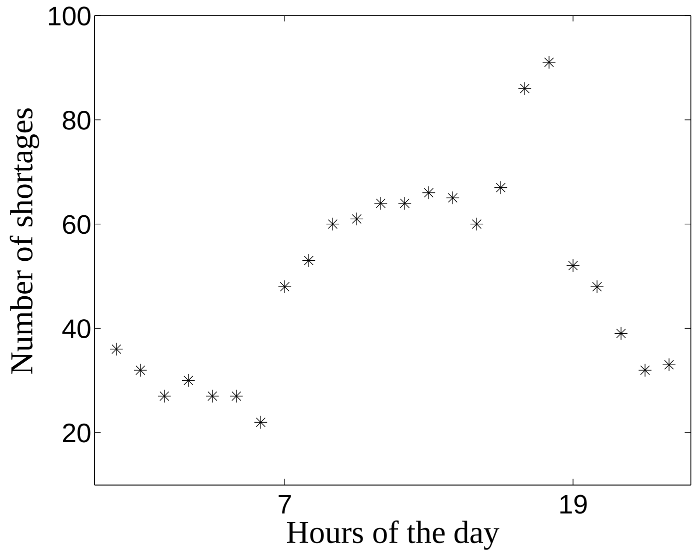

Figure 4.6: The number of times when the load was not fully supplied with wind power as a function of the time of the day. MGC_{wind} is 10 and storage capacity *MSC* is 1.

4.4 Comments on the cases

Solar power as the only source, case 1, for remote systems is obviously more suitable for supplying day time load than night time load as can be seen in Figure 4.5. Unfortunately, systems with only daytime load are rare and therefore such systems are not an option. Solar power may be used for systems where the main load is during day time and during the dark hours it has to be combined with another source or storage.

Wind, see case 2, is more suitable than solar but still not sufficient. The number of non-supplied hours over the day is less for wind as compared to the case with only solar power.

A storage in combination with solar gives a higher increase in the availability than with wind because of the higher regularity of solar power, cases 3 and 5. For cases 4 and 6 the sizes of the storage are so large that a full storage will cover the complete load during the night which explains the high availability for case 4.

The benefits of a small constant power source are investigated in cases 7 - 12. The benefits are great especially in combinations with the regular solar power. As can be seen in the cases a MGC_{hydro} above 0.1 only gives minor improvements of the availability. The reason is that the hydro power then will cover the load during the night.

There is only a small change in availability when a storage is added to a solar/hydro or wind/hydro system since the hydro power with its reservoir introduces a storage as can be seen in cases 13 and 14.

Using wind and solar in the same system is favourable as can be seen in the last five cases. The optimal relation between solar and wind power can be found in Paper V and optimal is close to what has been used in the last cases. In general, more sources and storages give better availability.

Chapter 5

Load Control

The "fuel" from renewables are in many cases for free which gives new challenges for control of the system to maximise the benefits of the energy sources. For frequency and voltage control of a system a continues controllable load (CCL) can be used. A CCL is a load that can control the frequency and voltage of the system continuously. A CCL is typically a load where storage is possible or the output may vary without affecting the usefulness of the load. A typical load is a pump that is fed by a frequency converter. To enable control of both active power (frequency) and reactive power (voltage) a frequency converter with an active rectifier is needed.

5.1 Frequency Control

The benefits of using a CCL for frequency control have been investigated in Paper V. The paper shows that significantly less energy will be wasted. However, it will have a small negative effect on the availability of the more prioritised loads. The size of the CCL will determine the wasted energy and the availability of the loads. A too large CCL will utilise more of the energy whereas the availability of the prioritised loads will become lower because there is a need of a minimum load of the CCL. On the other hand a too small CCL will have less effect on the availability and more energy will be wasted.

The CCL has to handle both load changes and changes in the generation. The generation is stochastically varying as has been discussed in previous chapters. However, the short time variations in the generation are less as compared to the load changes where steps can be expected. Therefore the load changes will be dimensioning for the CCL. This has been further investigated in Paper VII.

5.1.1 Other control strategies

To get a stable frequency in an electric power system the load and the generation have to be equal at any instant. This is normally done by controlling the generation but assumes good availability of power [69]. Controlling the frequency in large electric power systems is a well investigated area. In large systems it is not enough to use only one frequency controller for the complete system [75] and therefore many production plants are equipped with frequency controllers.

In an isolated power system, based only on renewables, generation frequency control will lead to an inefficient use of energy to obtain a control margin. In these systems, where the availability of renewables is low, the control can be carried out by a storage system. Several different systems, all based on control by the storage, are discussed in [76]. There are several storage technologies available such as [77, 78]:

- Batteries
- Flywheels
- Pumped hydro
- Super conducting Magnetic Energy Storage
- Compressed air
- Capacitors
- Regenerative fuel cells

Many of these technologies are not suitable for small systems or systems with low maintenance demands or are very expensive. Therefore battery systems are most commonly used and proposed for isolated power systems in developing countries. For example the use of batteries is discussed in [79, 80] and it showed good response times but many charge/discharge cycles shorten the lifetime of the batteries and increase the losses. Even if batteries are one of the cheapest and mature storage technologies they are a significant part of the installation cost and in some cases the single most costly part in the system [81]. The maintenance demands are also rather high [11].

Another method of system control is load shedding. However, load shedding is normally used as a last resort since it affects the availability and thereby the usefulness of the load [82]. A load shedding system also requires electronic equipment for the load.

One frequency control method used in isolated power systems is the use of a dump-load [83]. This method gives a good response time but waste energy. The energy is not always totally lost since it may be used for heating purposes. However, there is a limited need for hot water in most developing countries.

5.1.2 Investigated system

The system that has been investigated can be seen in Figure 5.1. It consists of a small power system supplied by a synchronous generator (P_{sg}), solar panels (P_{solar}) and perhaps another source (P_{other}) . The loads are adjustable resistive prioritised loads (P_{pri}) and a CCL (P_{CCL}). The CCL consists of a frequency converter supplying an asynchronous machine that is connected to a load with a quadratic torque speed dependency e.g. a pump.

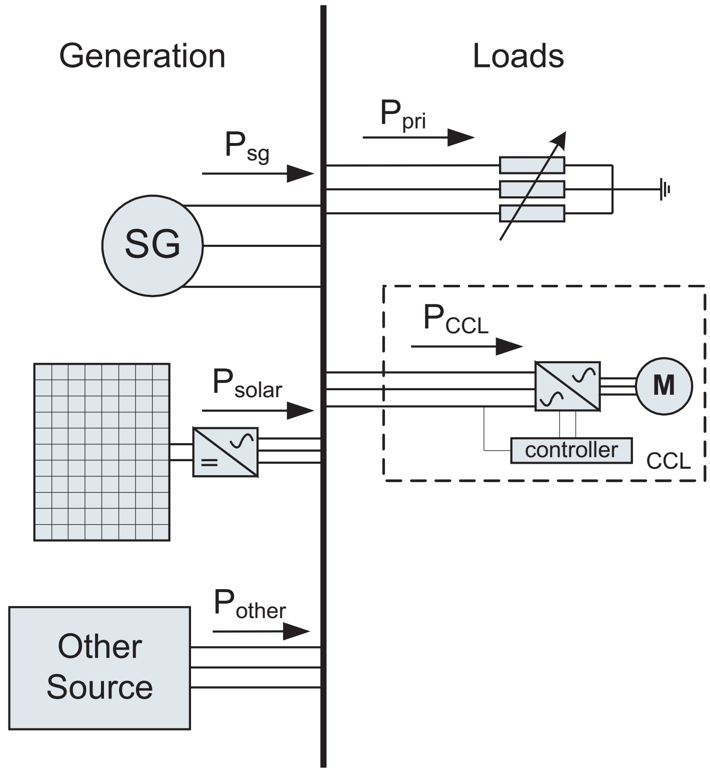

Figure 5.1: The studied system for frequency control. The system consists of a synchronous generator, solar panels and loads including a CCL.

5.1.3 System modeling

The power system was modelled using only the mechanical equation, the so-called swing equation [69], which can be seen in Eq. 5.1.

$$J\omega\frac{d\omega}{dt} = P_{gen} - P_{load} \tag{5.1}$$

where J is the moment of inertia of the system, P_{gen} is the total generation, see Eq. 5.2, P_{load} is the total load of the system, see Eq. 5.3 and ω is the angular frequency. P_{load} consists of both the loads (P_{pri}) and the CCL (P_{CCL}).

$$P_{gen} = P_{sg} + P_{solar} + P_{other} \tag{5.2}$$

$$P_{load} = P_{pri} + P_{CCL} \tag{5.3}$$

The power consumption of the CCL is related to the frequency on the load side of the converter (f_2) according to the simplified Eq. 5.4. k is a constant for the pump, see Eq. 5.6, and s is the slip. Since the slip is proportional to the frequency, with constant flux and quadratic load behaviour, the relation in Eq. 5.5 has been used. Here s_n and f_n are the nominal slip and frequency of the induction motor whereas P^n_{pump} is the nominal power of the pump.

$$P_{CCL} = k(f_2(1-s))^3 \tag{5.4}$$

$$s = \frac{s_n}{f_n} f_2 \tag{5.5}$$

$$k = \frac{P^n_{pump}}{(f_n - s_n)^3} \tag{5.6}$$

5.1.4 Controller design

A two-degree-freedom controller using the loop shaping method was derived [84]. Naturally there are several other methods of designing a controller, like deadbeat and hysteresis control [85], but they were not considered as the scope of the this thesis is to show the the potential of the controller and not to find the optimal tuning.

Loop shaping is a method were the step response is shaped by the design of the controller. The desired shape is the response for the closed loop system that is a low pass filter. This can be done by solving Eq. 5.7 in the Laplace plane (p is the Laplace operator).

$$\frac{FG_{ol}}{1+FG_{ol}} = \frac{\alpha}{p+\alpha} \tag{5.7}$$

where F is the is the controller, G_{ol} is the transfer function of the open loop system and α is the speed of the system, expressed as the pole location.

To be able to derive the controller the system (G_{ol}) needs to be linear and therefore Eq. 5.1-5.6 were linearised. The transfer function (Eq. 5.8) was found using Laplace transformation.

$$G_{ol}(p) = \frac{A_{2o}}{p - A_{1o}} \tag{5.8}$$

where

$$A_{1o} = \frac{4\pi f_o T_{mo} + P_{solaro} - P_{loado} - k(f_{2o} - \frac{s_n}{f_n} f_{2o}^2)^3}{2H_o S}$$
$$A_{2o} = \frac{k f_o 3(f_{2o} - \frac{s_n}{f_n} f_{2o})(1 - 2\frac{s_n}{f_n} f_{2o}^2)^2}{2H_o S}.$$

The subscript “o” for the parameters are the values in the operating point. H is the total inertia of the system. In this case the inertia is the same as for the generator H_g since the inertia of the CCL does not have any impact on the system inertia. T_m is the torque of the axis of the generator while S is the total power of the system. Figure 5.2 shows the frequency controller which consists of a proportional (Kp), integral (Ki) and active damping (Ra) constants according to Eq. 5.9-5.11. α_f determines the bandwidth of the closed loop system for frequency control. The active damping is set to have the same response time as the rest of the system [84]. The controller is reversed since a higher system frequency, f, shall be corrected by an increase in load frequency, f_2, and vice versa. This is the opposite of normal motor drives and can be realised through a change of signs of the frequency error and the active damping term, see figure 5.2.

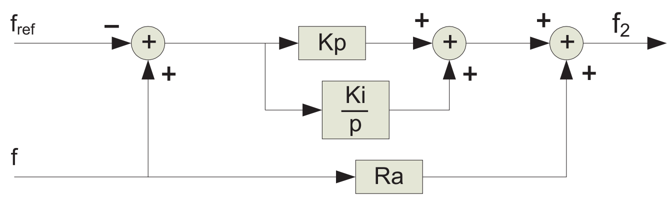

Figure 5.2: A two-degree-freedom controller for a reversed drive of a CCL.

$$K_p = \frac{\alpha_f}{A_{2do}} \tag{5.9}$$

$$K_i = \frac{\alpha_f^2}{A_{2do}} \tag{5.10}$$

$$R_a = \frac{\alpha_f + A_{1do}}{A_{2do}} \tag{5.11}$$

The subscript “do” is for the design operating point.

5.1.5 Stability investigations

In Paper VI a stability investigation of the system was performed. Changes in the inertia and the load were investigated. This since they are the parameters that are likely to vary most in the system as they are related to the load changes. The load changes are related to human behaviour which is hard to predict. Figure 5.3 shows the poles of the system when the inertia is changed from half to twice the design value.

The analysis shows that the system can be considered well damped even if the system has twice the designed inertia. Since a too low estimation of the system inertia only will give a slower system the inertia should be overestimated to avoid the risk of instability.

Figure 5.4 shows the movement of the poles when the prioritised loads are changed. The figure shows that if the load varies above the designed operation point there is a risk of instability. Therefore if there are uncertainties in the load parameters they should be overestimated.

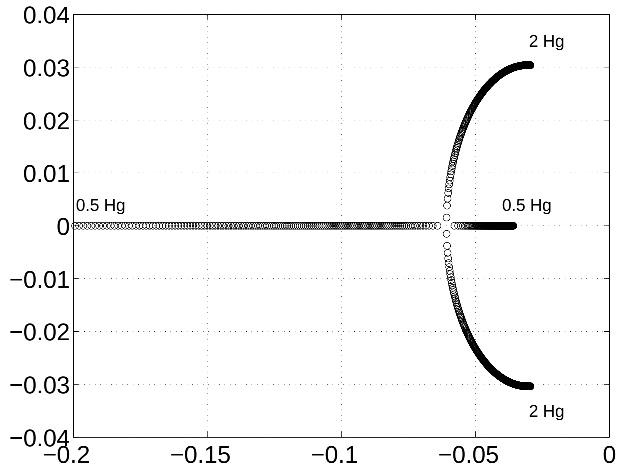

Figure 5.3: The movement of the poles when the inertia is changed from half to twice the designed value.

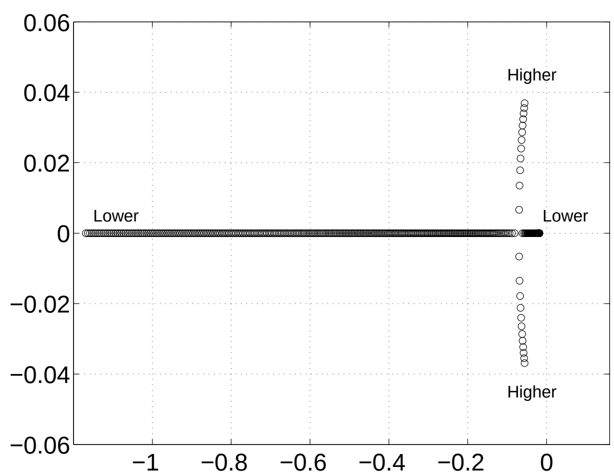

Figure 5.4: The movement of the poles when the load is changed. The load is compared with the designed load

There are several other factors like the parameters of the generator and the rest of the system that may affect the stability of the system. However, the other parameters are often better known or are of less importance.

5.1.6 Verification of the controller

The controller was verified through simulations and laboratory studies. The simulations were done using the software package PSCAD/EMTDC [86] whereas the laboratory studies were performed using the network model at Chalmers University of Technology [87].

As a verification load changes were made in steps. Steps in the applied torque were only done in simulations because it was hard to perform large steps in the laboratory model. Small steps were done but the frequency deviation could not be seen due to noise. The problems with steps in the torque are further discussed in Paper VII.

The production source used during the verification was a synchronous generator connected by a stiff axis with a flywheel to a DC machine. The DC machine worked like a turbine and produced a torque. Together with the flywheel and generator it also contributed to the inertia of the system. The load of the CCL was an induction motor connected through a stiff axis to another DC machine which operated as a pump i.e. had a quadratic torque speed dependency. As prioritised loads purely resistive loads were used. Data of the generator and the load of the CCL can be found in Table 5.1

Table 5.1: Data of the generator and CCL load used in the study.

	Generator ASEA GA 84N 1976618	CCL load ASEA MBG 180L-4
Rated Voltage [V]	400	380
Rated Current [A]	108.3	62
Rated speed [rpm]	1000	1450
Total inertia [s]	5.5	3
cos φ	1.0	0.81

The behaviour of the proposed controller was tested through simulations that were validated by laboratory experiments. Data of the system are available in the appendix. The speed of the controller (α_f) was set to 1.0 to get a stable operation. The operating point was set to a load where the CCL was working in its lowest point (10 % of the total capacity) according to the recommendations in Paper VI.

For voltage control a standard excitation model (AC1A) was used in the simulations. The complete frequency converter was implemented in the simulation model. The valves used were ideal diodes whereas the power electronic switches and the switching signals were created by PWM.

For the laboratory validations an ABB frequency converter ACS 800 was used [88]. The built-in control system was used and the programming was done with the smallest and the cheapest programming module (only 15 blocks). For everything else standard implementation was used. In Figure 5.5 the generator, the flywheel and the DC machine working like a turbine can be seen. In Figure 5.6 the motor used as a load of the CCL can be seen. The DC machine used as the load can also be seen in the figure.

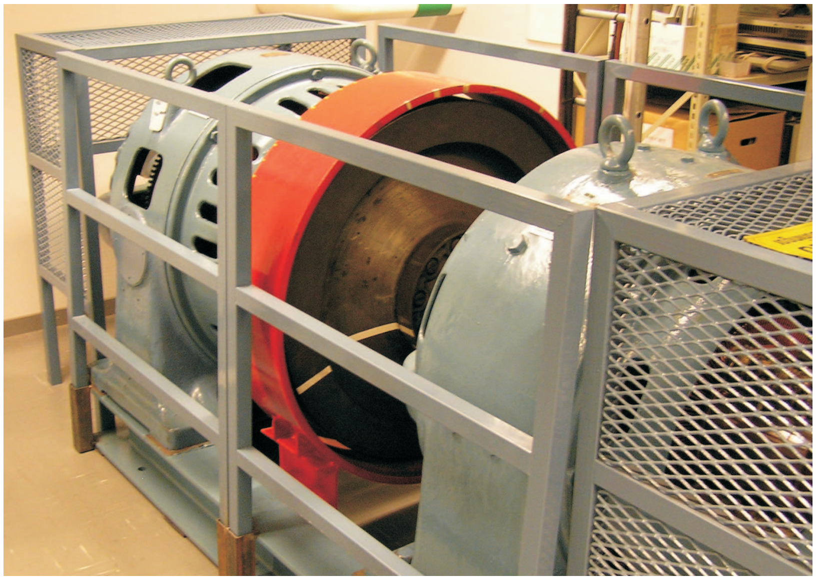

Figure 5.5: The generator, flywheel and DC machine used in the measurements.

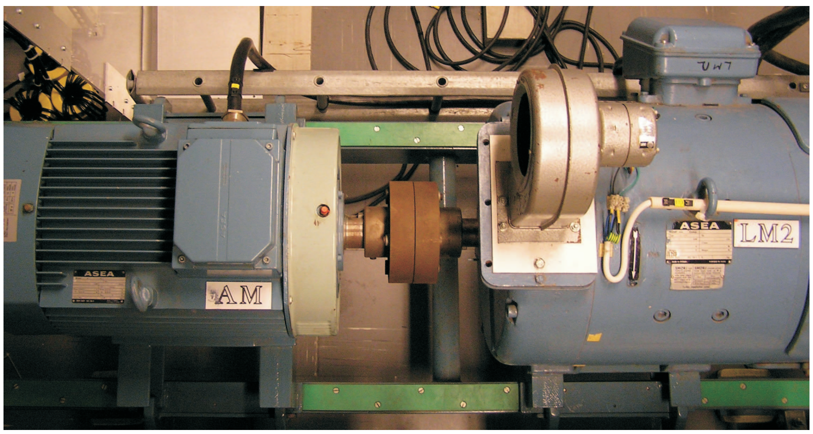

Figure 5.6: The asynchronous machine and the DC machine used as load of the CCL.

In Paper VII the results of the simulations and the measurements are compared both when a small and a large load are connected and disconnected. The results show good agreement both for the frequency deviation and the time it takes until the frequency has stabilised.

5.1.7 Discussion

In Paper VI the behaviour of the CCL as compered to other more conventional frequency control methods is investigated. The investigated methods are beside the CCL a diesel generator and a pitch controlled wind turbine. The study showed that a CCL is fast and can give a frequency control that is better as compared to conventional frequency control systems.

5.2 Voltage Control

To achieve a stable voltage in a power system the reactive power has to be in balance in the system. Normally loads are inductive, e.g. motors, and therefore reactive power have to be produced to get the balance. This is mostly done by the excitation system of the generators. However, the possibility to produce reactive power is constrained by the limits of the field current, armature current and the under-excitation. This is further discussed in Paper VIII.

Today frequency converters are often equipped with an active rectifier to minimise the harmonic emission and the need for reactive power. The rectifier can then be working as a shunt connected Voltage Source Converter (VSC). The use of shunt connected VSCs is a well studied area for higher voltage levels. For high voltage applications this concept is used for both voltage control and stability purposes and is often called STATCOM [89]. At distribution level (10 kV) it is called D-STATCOM and can be used for voltage control in weak grids [90] and to avoid flicker [91] and voltage dip mitigation [92]. Voltage control is normally not performed at lower voltage levels due to economic reasons.

5.2.1 Investigated system

The system that has been investigated for voltage control is shown in Figure 5.7. The small power system is based on a small synchronous generator, a CCL, adjustable resistive, inductive and capacitive loads. The generator has a constant excitation.

The prioritised load (Q_{pri}) varies related to human behaviour. The CCL (Q_{CCL}) may both consume and generate reactive power whereas the solar panel (Q_{CCL}) can neither produce nor generate any reactive power.

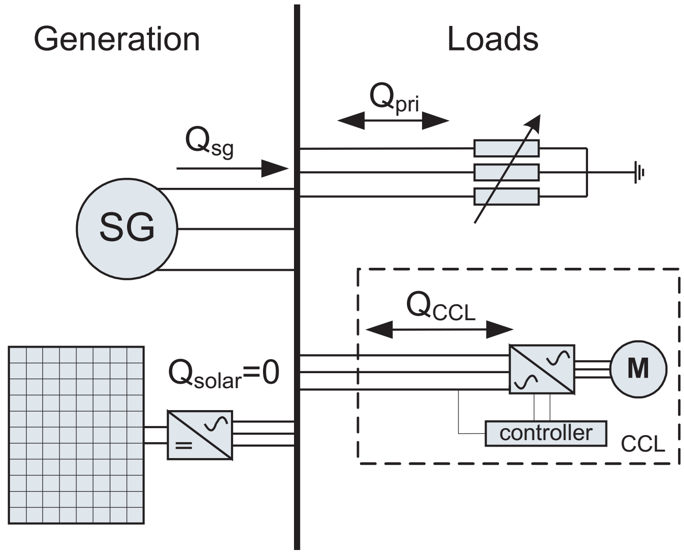

Figure 5.7: The system that is considered for the voltage control, supplied by a synchronous generator. The loads are adjustable resistive and reactive loads together with a CCL. The arrows indicate the direction of the reactive power flow in the system. Q_{sg} is the reactive power produced by the generator.

5.2.2 Controller design

The voltage controller can be designed by considering a system having a frequency converter modeled as a current source that gives a certain voltage (U) according to Figure 5.8.

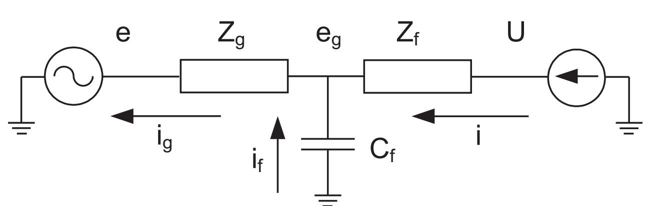

Figure 5.8: The system considered for design of the voltage controller. e_g is the voltage to control, C_f is a capacitor, Z_f is the filter impedance and grid is represented by a voltage source e and a grid impedance Z_g.

By applying Kirchhoff's current law in the center node, the transfer function, Eq. 5.12, can be obtained. This is further explained in Paper VIII.

$$\frac{e_g^{dq}}{i^{dq}} = \frac{1}{sC_f} \tag{5.12}$$

The parameters were determined according the same method used for the frequency controller, see section 5.1.4 [84]. The parameters of the controller, proportional gain (K_p), integration gain (K_i) and active damping (Y_a) where α_v determines the bandwidth of the voltage controlled system were determined according to Eq. 5.13 and 5.14.

$$K_p = Y_a = \alpha_v C_f \tag{5.13}$$

$$K_i = \alpha_v^2 C_f \tag{5.14}$$

5.2.3 Verification of the controller

The controller performance was test through laboratory tests and simulations. The tests were done in the network model at Chalmers University of Technology [87], while the simulations were done using the software package PSCAD/EMTDC [86]. The rectifier was modeled as a controllable current source and thereby only the voltage controller had to be built in the simulation program.

The same generator as used to verify the frequency controller was used. However, since the generator is too large the short circuit power were limited by some inductances which is further discussed in Paper VIII.

Three different tests were made to verify the voltage controller, a voltage step response test, a load change test and a start of an induction motor. The parameters were set to get an acceptable voltage quality. Fulfilling standard requirements is one way to achieve an acceptable voltage quality. Since the same standards can not be expected for all autonomous systems, one example as a representative standard was used, namely the Swedish standard [93]. The controller could easily meet the requirements as shown in Paper VIII.

To be able to study the behaviour of the controller step change was initiated in the prioritised load were performed. A start of a small induction motor was also made. The size of the induction motor was kept small because of the large start currents. The response in the voltage and the change of the reactive power of the CCL can be seen in Paper VIII.

5.2.4 Discussion

The voltage dip is dependent on the size of the applied disturbance. A relative small motor will at start cause a relative large dip and therefore soft starters are recommended for the start of a large motor.

For off-the-shelf converters, as the one used in this study, some delays and limitations are introduced. The main delays are caused by the fact that the controller uses the rms voltage as input instead of the instantaneous value. A control method based on vector control could be used with only a modification of the software on the line card. This would increase the speed significantly to only a few milliseconds [92]. However, since only reactive power will be injected a phase shift will arise that can effect loads like thyristor controlled equipment [58]. This problem arises because the available off-the-shelf products are not adjusted for this purposes. However, they can with only some small modifications.

By the use of the built-in control of the converters other features can be utilised, like harmonic reduction and supervision of the system without any additional programming.

5.3 Frequency and Voltage Control

Frequency and voltage control as described in section 5.1 and 5.2 do not utilise the same part of the frequency converter. Therefore it is suitable to combine them in small systems. As a result the system will include both control of the active and the reactive power from the CCL. The complete system considered for frequency and voltage control is depicted in Figure 5.9.

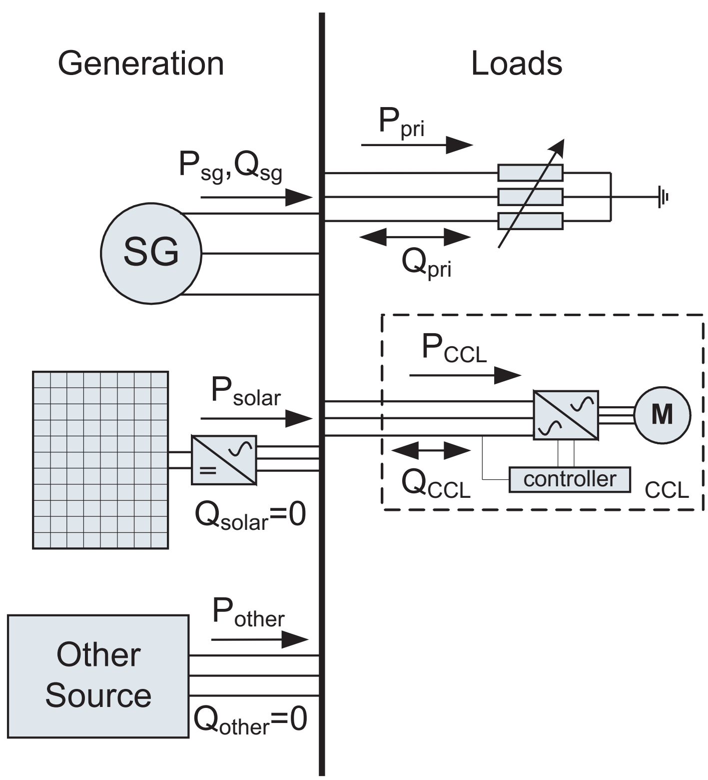

Figure 5.9: The system that is considered for voltage and frequency control. The arrows indicate directions of the power flows in the system.

Both the controllers previously described have to be implemented in the same program (maximum 15 blocks in the frequency converter that is used). In this study the software could be implemented in only 12 blocks. Figure 5.10 shows the response after the connection of a load. The load is a heating fan that gives a 40 % change in the active power of the total system load.

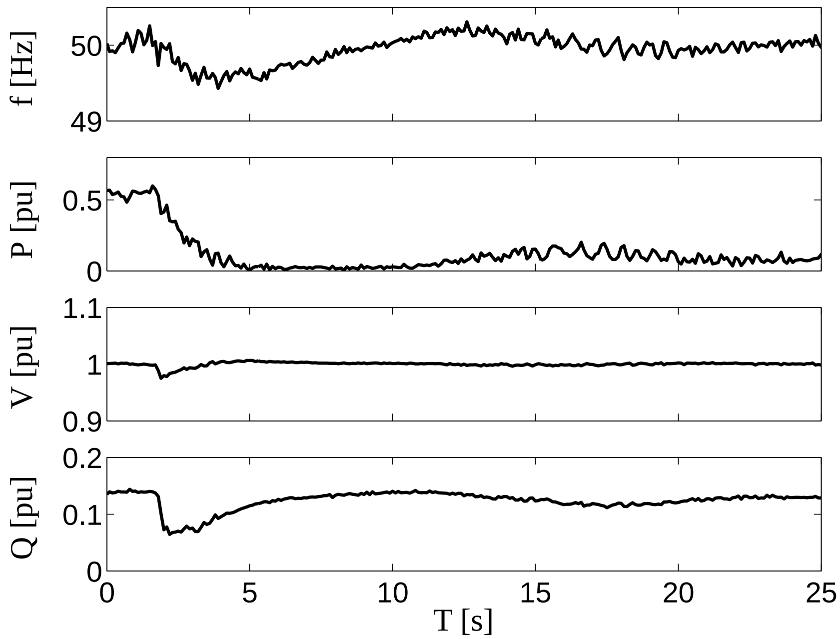

Figure 5.10: The response of the frequency (f) and voltage (V) of the system together with active (P) and reactive (Q) power of the converter after a load connection that corresponds to $\sim$ 40 % of the total system load.

As seen in the figure the voltage recovers was much faster than the frequency recover. The frequency deviation was around 0.5 Hz (1 %) and the voltage deviated 2.5 %.

It is possible to control the frequency and the voltage by the same frequency converter since the time scales are different. The voltage control is faster than the frequency control and therefore they can be controlled individually. The capacitor in the frequency converter also contributes to the decouple the controllers. The load of the CCL will be more or less independent of the voltage in the power system at least for shorter variations.

5.4 Further applications of load control

The use of load control for frequency and voltage is not only possible for autonomous power systems based on renewables. Load frequency control is suitable also at disturbances and for island operation. Load voltage control, however, has a wider range of application.

5.4.1 Load frequency control

If the frequency in a large power system will drop below a certain value (48.8 Hz in Sweden [94]) load shedding is used. Then large areas will be disconnected to save the system. By allowing certain loads to reduce their consumption of active power the system may be saved from a blackout without affecting the customers. Many loads can be temporarily disconnected without causing too much trouble for the customers, such as heating, ventilation systems in commercial and residential buildings. Reducing the heating or the ventilation system for a short time hardly affects the indoor climate because the time constant for these systems are in the range of hours. The reduction of the loads could be done before the load shedding is activated. The reduction can be gradually done to get the same effect as the other emergency measures, e.g. emergency generators and electric heaters.

Island operation is of interest not only for remote areas and geographical islands. Today industries with in-house generation are operated in island mode when there is a risk of disturbances originating from the main grid. There are several reasons for this. One One is to have the possibility to continue the production during blackouts and the other is to protect the systems from voltage dips. The electricity is typically produced by burning waste from the production. Therefore the generation may vary independently of the loads and a load that works like a CCL can be used as buffer if the margins are low.

Island operation is considered not only for industrial operations but also for cities and other predefined areas [95]. Then the local generation capacity will be used which may be of different kinds, e.g. CHP, gas turbines and renewables. The load may also contribute to the frequency control. Suitable objects for this kind of control would be pumping stations like sewage-treatment plants.

5.4.2 Load voltage control

The load voltage control can be used practically everywhere where frequency converters with active rectifiers are installed. By allowing the frequency converter to supply the grid with reactive power voltage control can be obtained. However, there is a limit in the capacity of the converter which may affect the range of the control. A larger rectifier part can be an option instead of installing other voltage control equipment.

Chapter 6

Conclusions and future work

6.1 Conclusions

In Africa there is no lack of energy sources. However, there is a lack of infrastructure to handle the available energy. By a suitable infrastructure great improvements can be achieved for both the people and the environment.

A model for simulation of solar radiation based on cloud observations has been presented. The advantages of the model are that there are no geographical restrictions and that there is no need for solar radiation measurements. The model requires cloud coverage observations, which often are easier to obtain over a longer period. However, there is no need of continuous data series. A stochastic model to generate cloud observation series for use in simulations was also developed. In the model the year can be divided into several parts, if needed, depending on the climate and the data.

A model for simulating wind speed time series has been proposed having a limited need of site-specific wind speed measurements. The model can also be adjusted to the altitude of the wind turbine and in a simplified way it can handle local conditions like different wind behaviour for different wind directions. When the wind speed curve is known the model can easily be combined with any wind turbine.

With solar power as the single power source, a higher availability than 50 % will never be reached, independently of the installed power. By adding a small part of water flow into the system to cover the low load hours the availability would increase significantly. Use of only wind power gives a maximum availability of 65 % but in combination with small scale hydro power and/or storage capacity even a higher availability can be achieved. The solar based system shows a more regular behaviour than for wind power and thereby storage can be more efficiently used. If a storage is not used the lack of energy will be evenly distributed during the day. If a storage is used most problems with insufficient energy supply for an industrial based load characteristic are expected to occur during the afternoon. The studies have shown that it is possible to build power systems without diesel generators. For systems based entirely on renewables it is necessary to provide some over-capacity, either by storage capabilities or combinations of energy sources, in order to ensure the availability of the system.

Sometimes the entire load can not be covered by the generation. By the use of active load shedding of 10 % of the load the annual shortages could be reduced with up to 20 %.

The required availability depends on local and economical conditions. Therefore studies of the local conditions are needed before the design of a system at a specific site.

Since an over-capacity is needed a lot of energy will be wasted. By introducing a CCL based on a frequency converter significantly less energy will be wasted. However, a CCL will decrease the availability some due to the requirement of a minimum power to the CCL. A CCL can also be used for frequency and voltage control of the system.

A method of load frequency control by a frequency converter is proposed. It has been shown that a stable frequency controller easily can be obtained using well known control theory, with only minor modifications. The controller can easily be implemented in standard off-the-shelf products like a frequency converter. The frequency deviation due to load changes is less using a CCL as compared to other more conventional frequency control methods. The control method has been tested both in a simulation environment and by laboratory experiments. For small systems the cost of a CCL is expected to be in the same price range as dump loads but the energy use will be better. If frequency converters already are installed there will be no extra cost for this frequency control method.

If a frequency converter has an active rectifier the converter can also be used for voltage control. It has been shown that a frequency converter is well suited for voltage control in energy systems built on renewables. The controller will be comparable to other voltage control systems. Additionally, it will not require any new investments in the systems. The new function of the frequency converter will not prevent the utilisation of all the other already built-in features, like harmonic reduction.

Both the frequency and the voltage control can be utilised in all power systems. The frequency control is applicable both for mitigating disturbances and for island operation of industries and regions. The voltage controller can be used everywhere in the system where voltage control is needed and frequency converters are installed.

It has been shown that an autonomous power system based on renewables can be built and controlled by the use of available off-the-shelf frequency converter and with some small modifications the behaviour of the control system can be improved.

6.2 Proposals for future work

The use of systems based entirely on renewables is an interesting area where a lot of research needs to be done. Below some topics are outlined as proposed future work.

Today most turbines are built for systems connected to a grid and therefore the energy output is maximised, However, for autonomous power systems other wind turbines are needed. Those turbines should be designed for maximum availability. Consequently they need to be able to efficiently harvest low wind speeds.

As has been shown in this thesis that the potential of autonomous power systems is great and therefore it would be interesting to build a test system in a developing country to test the ideas. Before that it is important to investigate the social acceptance of introducing such a system.

Load control has been shown to have a great potential for autonomous power systems based entirely on renewables, but also in other power systems this could be of interest. Therefore an investigation of its full potential would be interesting.

Building an autonomous power system is just the start. A large grid will naturally increase the availability even further. This could be reached by interconnections between several smaller systems. The control of several interconnected autonomous power system is the topic for other research projects.

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