CHALMERS

Development of Computer-based Simulation for Wind Diesel Systems Optimisation

Master of Science Thesis
"Environmentally Sustainable Process Technology" Master's Programme

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Göteborg, Sweden, 2007

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THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

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0 ABSTRACT

With the emergence of renewable energies many technical questions about the efficient integration of these in the existing mixes of technology raise. Renewable energies are characterised by environmental savings regarding Green House Gases emissions, and by economic savings corresponding to the running costs linked to fuel purchase, transport or even waste treatment or disposal. The most emergent of them, developed within the last years, is the wind energy.

Geotropic wind currents and movements constitute an abundant and free resource in many places. Moreover, wind power generation is non-polluting. Integrate wind turbines in remote areas could be therefore a solution to replace conventional technologies such as fossil fuels combustion.

In large mixes, the variability of wind power sources could be carefully controlled with adapted electrical equipment and grid connection. Where there is no central grid it is even harder due to reduced mixes of technology. These mixes are often limited to only one power source in many rural areas of the developing countries, islands and other remote places.

The technical feasibility of wind power integration has to be carefully considered as a wish to optimise existing Wind Diesel Systems and also to increase the wind energy penetration in future systems. Existing wind diesel systems show the interest to integrate wind energy but show also the need to design these systems appropriately.

Wind turbines output power short time fluctuations are significantly higher than they are for other energy supplies and can perturb the whole system. The diesel engines are able to manage load variations, but not high variations such as sudden decrease of wind without an efficient system of control and regulation. This system of control could be improved by studying the effect of the wind variation on the system behaviour in the aim to regulate further more both combined wind turbines and diesel engines.

Study the effect of wind turbulences on Wind Diesel (WD) systems remains on the analysis of the system characteristics such as the penetration of wind power, the quantity of produced power by the diesel engines and the quantity of rejected power. These data can be followed with different time frames according to available data in saving computer system. These time scales are often hourly based for wind resources calculation but could and should be secondly or minutely based for further analyses.

Detailed technical analyses about WD systems characteristics show the possibility to increase the wind penetration with a diesel set-up controller efficiently defined. Limiting values to switch off and on the respective gensets have to be determined to ensure that the generators do not switch off too fast. This evolves that one or two engines should run at low partial loads during 25 % of their running time, and this confirms the interest to develop Low Load Diesel.

Predict wind diesel systems reaction to short term wind fluctuations is a good approach to find adapted and efficient operation conditions to use as much as possible wind energy and to minimise possible negative effects on diesel generators while ensuring a reliable power quality. Further study directed in this sense about strategies implementation will adequately complete this one which brings the keys to follow the behaviour of WD systems and which allows to determine the limiting constraints to raise the wind penetration in existing reduced mixes of technology. This responds thus to the wish to increase the development of WD systems, particularly where the fuel dependency could or should be reduced.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Master Thesis Context

The thesis was achieved during five months (October 2006 to March 2007) within the company "Lahmeyer International" GmbH in partnership of Chalmers University of Technology through the "Electric Power Engineering" department, belonging to the division of "Energy and Environment". It was chosen that the master thesis will not be done directly within the "Chemical and Biological Engineering" department (to which belongs the "Environmentally Sustainable Process Technology" master programme), since the scope of the thesis corresponds more appropriately to the "Electric Power Engineering" department. That was relevant since Mr. Ola CARLSON, supervisor from the previously named department is expert in wind energy and electric power systems.

"Lahmeyer International" is a famous company of consultant based in Germany (in Bad Vilbel, close to Frankfurt am Main), realising projects in developed and developing countries, in three fields of predilection: Energy, Water and Transportation. Further Information about the company can be found in appendix 1. The energy division contains several departments including the "Renewable Energies" department and the "Wind Energy" department, separated few years ago to the previous one as a response to the increasing demand of wind power installation and exploitation.

This master thesis was elaborated within the department of "Wind Energy" led by Mr. Bungo EZAWA and completed under the supervision of Mr. Christian DAHLE. Before the five months devoted to the research for this thesis, three months were spent to actively participate to department's projects and to study in the meantime the procedures for wind parks development. The report written during this first period, named "Wind Park Projects Development" [1], can be read for further details about wind power plants design and installation.

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1.2 Subject Background

Renewable energies are constantly developed as a way to reduce the impact of electricity production on the environment. This aim was promoted by the Kyoto's protocol with the United Nation Framework Climate Change Convention. One of the renewable energy technologies consists to the conversion of the kinetic energy of the wind into electrical energy.

Wind is a natural, renewable and non-depleting resource. Wind is produced by temperature and pressure gradients, resulting of sun radiation on the earth absorbed by the air. Air naturally moves from high-pressure zones to low-pressure zones, trying to equalise the air pressure. This air movement creates surface winds. Due to elevation, topography, surface roughness, and location, many areas present a high potential for wind power production.

Wind energy technologies are developed all around the world. Wind parks are installed and exploited for numerous applications such as household, business, or industrial. The electricity can be used directly by the turbines owner or can be injected to the grid and sold to the utility, with appropriate grid connection and Electricity Purchase Agreement.

Another application of wind energy is developed to supply remote areas where there is a good wind potential. The integration of wind energy in such reduced mix of technologies, composed of diesel and wind power supplies, is a challenge of nowadays. It is even more relevant in some worldwide regions, where the population density is too low to justify a centrally supplied grid, because of high distances and low demand requirements. The grid extension is in these circumstances not cost-effective. Decentralised energy generation is the most appropriate solution.

Integration of wind energy in remote areas could be even more interesting where the electricity production is based exclusively on diesel combustion. The savings on the running costs, mainly corresponding to the fuel purchase and transport, could be justified. Existing wind diesel systems show the interest to integrate wind energy but show also the need to design hybrid systems appropriately and carefully.

In Wind Diesel (WD) systems design project, high wind penetrations are often not feasible since that could influence too much the stability of the grid power quality. And low wind penetration systems constitute a proven technology, but the amount of fuel savings are sometimes reduced in such small supply systems, and make the project difficult to be financed and followed.

Electricity supply systems, grid-connecting or stand-alone, have to meet a good power quality. In opposition to grid-connecting system, in a stand-alone system both load and supply variations are closely dependent, and there is no centralised stable supply to ensure the required grid stability.

The variability of the wind makes the challenge even more difficult. Many strategies have been already developed, installed and promoted in order to minimize the effect of wind penetration on the power quality and also to maximize the use of wind energy. The most known strategy is to store energy in a bank of batteries. Control strategies appeared in the recent years as the wish to increase electricity production and usage, through the wind penetration, in a whole small off-grid system.

1.3 Problem Statement

With the emergence of wind technologies, wind diesel systems are one of the most developed types of hybrid systems. The challenge is not only technological, it should be completed by a system behaviour prediction and an evaluation of the economic performance. An advanced economic modelling capability allows to optimise the design by studying carefully the variability of the load, the availability of renewable resources, fuel prices; maximising efficiency or flexibility; minimising fuel use and emissions; figuring critical operations for maintenance; and considering the constraints imposed by legislation, permits, incentives and subsidies.

All of these points mentioned above are necessary conditions for hybrid systems development. However, Wind Diesel Systems at a low wind penetration, linked to a low level of control strategy, are often not reliable enough to ensure significant savings and benefits in respect to fuel purchase prices and emissions. The difficulties to predict the system behaviour represents a limit to the possibility to increase the wind penetration in current WD systems. However, if the wind penetration in a system is maximised, the savings would increase, and wind diesel projects may gain in relevance and consideration. At the moment, it seems therefore to be a priority to study the effect of wind fluctuations on the system at a small time scale in order to design appropriate control system.

1.4 Aim of the Thesis

This thesis will focus on the installation of wind diesel systems in remote areas, like it is often the case in developing countries, where low electricity demand is observed but where, most of the times, a small power station based on petroleum combustion is used to produce electricity. The general aim of the thesis is therefore to study the advantages and disadvantages of the diversification of generation sources by studying the integration of wind power into an existing grid currently supplied by diesel stations only. In such reduced mix of technology, i.e. composed of wind and diesel power plants, the savings regarding emissions and fuel purchase prices can be well figured out. However, the precise evaluation of the required figures is depending on the stability of the system, which is not easy to predict. That is why the control system should be improved in order to regulate efficiently the combination of wind turbines and diesel engines. That can be done by studying the effect of the wind variation on the system behaviour.

Wind turbine output power fluctuations are significantly higher than they are for other conventional energy generation technologies. The effect of these wind fluctuations on grid stability is complex. This thesis will study the possibilities to integrate efficiently wind energy into isolated grids. This will be based on wind turbines output power and diesel power productions study, with data at small time scale (10-seconds) in comparison to larger time scales (10-minutes, 1 hour). The effect of small variations will be study in order to get a good approach of wind diesel system design and operation. The results will be processed regarding to the main goals that the wind penetration should be as maximal as possible, and the effect of wind fluctuations on the diesel engines as minimal as possible, in consideration that high wind penetration systems generate higher savings and benefits but could have a strong negative effect on diesel generators.

The aim of this project is therefore to find optimal operation conditions in order to use as much wind energy as possible and to minimise possible damages on diesel generators while ensuring a reliable power quality.

2 WIND DIESEL SYSTEMS

The electrical network is composed of much additional electrical equipment in addition to power generators, consumer devices and the extra equipment required for the respective strategies. They are even more important for stand-alone systems. All the equipment and requirements of WD systems are presented in this part.

2.1 Electrical Requirements and Equipment in Isolated Grids

It is important to understand electrical mechanisms, technical operational requirements and limitations of power flows and stability in order to figure out how wind energy can successfully and effectively be integrated into a power grid. That is particularly important for stand-alone systems/isolated grids supply systems with small generators and low voltage levels.

The first goal to achieve is to provide the load with the power productions, while ensuring the second goal, which is more difficult: keep a good level and equilibrium of the voltage and the frequency, for consumer's comfort and safety conditions

2.1.1 Isolated Grids Characteristics

Such isolated grids are present in remote areas. There are mainly used when a large central grid is too far for rural or islands electrification purposes. There are numerous isolated grids in Africa, Asia, South America, in very large countries such as USA, and on islands all over the world. As a remark, hybrid systems are well suited to islands because of high wind potentials due to their topography and the proximity of see or ocean, even if the requirement of submarines cables in some cases could represent high investment costs.

- ***Load Characteristics***

The load, its level and profile, should be carefully assessed in consideration to the type of the demand and grid consumers (households, small or large industries, schools and dispensaries or hospital). Industries could consume significant quantity of reactive power while households consume mainly active power. World's Energy Consumption figures show that the developed countries have the highest consumption per person, whereas the lowest takes place in the third world. This difference is probably linked to the low level of access to central grids, and to the lack of industries in wide regions of the developing countries.

The load is a moving target and the variability of the demand can be even more important in weak grids, but in rural electrification, the type of load can be well determined. Daily or monthly results can be measured to define more precisely the load characteristics. Identify the worst cases, with the peaks and base load, is necessary. Typically the maximum peak load is in winter in cold countries, it happens often in summer in hot countries and tourists islands places.

The load characterisation is of first importance in feasibility studies, and a load management could be planned in order to reduce its variability if required. The aim is to ensure efficient load fulfilment with a robust and stable system. In this thesis the load was first considered as constant in order to analyse the sole effect of wind fluctuations. And in a second stage, the same protocol was processed with a variable load to taken into account the effect of the wind coupled to the effect of the load variation.

- ***Network Size***

The network is always designed in respect to the demand size. In the purpose of rural electrification, the extents of the grid are relatively limiting. It will mainly depend on the wind park location, which depends on the wind potential around the remote area, the available connection facilities, and possibilities. The distance between the wind park and the grid should be minimised, in consideration to the losses but also the investment cost for electricity transportation.

- ***Electricity Transport and Losses***

Energy losses are due to unavoidable resistive heating occurring in the transportation cables (overhead line or underground cable). The length of the cables linked to the grid extension, the voltage level and the current from of these cables are the main criteria for energy losses calculation. Energy transport is often achieved at medium voltage or high voltage. The high voltage required more electrical equipment for energy conversion, but it allows to reduce the losses during transportation. That is particularly necessary for long distances transport.

For isolated grids the total losses vary as a function of the grid extent, the level of the ongoing power flow. It has to be considered as an extra production, which should be added to the base load. Change or construct a new sub-station can constitute a major investment in a project. Wind park to less than 1km from a medium voltage line. The design decisions are based on the minimising electrical losses and capital cost, while ensuring the system is reliable and safe. If losses are reduced, electrical output is higher. Higher invest but higher incomes.

2.1.2 Power Quality Problems

Some possible troubles can appear during a change of behaviour of one of components of the electricity system. In WD systems, the main power quality problems are linked to the drastic increases and decreases in short time period of the voltage level occurring during shut-on and -off of the turbines or the diesel engines. Most common quality troubles are voltage sags, flickers, power interruptions. They can be traced to reactive power, which can be seen as the flow of voltage through the grid [2]. These effects are more or less important depending on the electric network weakness and the choice of devices.

- ***Voltage Sags***

Sags are basically short term reduction in voltage and can cause interruptions and damage to sensitive equipment and devices, designed to operate at constant voltage. Voltage variation is due to power fluctuation of supplying systems and demand. They are typically caused by fuse or breaker operation, motor starting or capacitor switching. A higher voltage than the grid in normal operation can damage the equipment due to over-perform, high internal losses and temperature rising exceeding the designed acceptable levels. A lower voltage implies transfers of reactive power over the network, due to high transmission losses, and that could imply a required extra power production.

- ***Flickers***

Flickers are due to rapid voltage variations occurring in an electrical grid. That causes light bulbs to noticeable flickers in light and also influences the other equipment interruption or malfunction.

It is provoked by sudden increases in load current. This quality problem can be even more significant in small weak grids, when large consuming machines are connected to a grid at a low of voltages. Asynchronous generators of wind turbines can also provoke sudden increase in load current during generator charging (what appears at the cut-in wind speed). The grid should be locally reinforced, generally to carry out the produced fluctuating current of a wind turbine (cf. paragraph about Transformers in the following "Electrical Equipment" part).

- ***Power Interruptions***

Power interruptions are due to high and fast voltage variations. The system can not anymore supply the load, with a drastic decrease of the supplied power or an increase of load current, and disconnect. The vast majority of power interruptions occurs in less than 30 seconds. That causes equipment interruption and can damage it.

- ***Harmonic Distortion***

The harmonic distortion is due to the power electronics such as rectifiers. The soft-starting turbines affect also the grid frequency due to the usage of extra thyristors. High level of harmonics on the network reduces the power quality and can cause overheat, equipment malfunction and disturb consumers. That is why the harmonic distortion should be less than 8%. Problems of harmonic distortions can be reduced with fitting filters.

However, like it was estimated in a feasibility of Lahmeyer this harmonic effect is not as preoccupying as the voltage and frequency variations in stand-alone systems. It depends on the system configuration and the electrical devices, which are in general carefully chosen or combined together in order to avoid the harmonic effect and to limit significant extra investment costs.

2.1.3 Controlled Parameters

The voltage and frequency are the two main parameters to control in order to fulfil the grid requirements. These parameters are directly related to the flow of reactive power trough the grid. For small isolated grids in concerned rural areas, the typical frequency is 50 Hz and the voltage level is from 11kV to 33 kV (it can be even of 400 V for smallest grids).

A Fault Level Analysis, made by the British Wind Energy Association to study the integration of wind energy in the electricity system [3], showed that the lower is the voltage level, the weaker is the system. The fault level is the current limit that a fault in the system appears. A fault is a quality problem linked to high voltage or frequency variation. A weak grid is a network, or a part of this one, where the fault level is low. For example, the fault level for 33 kV nominal system voltage is between 500 and 2,500 MVA, when it is only between 10 and 250 MVA for grid at 11 kV voltage level.

In weak grids, a fluctuation of 3 % of these parameters generates power quality troubles on the grid and disturbs or damages consumer devices, as explained in the previous paragraph. This value of 3 % was fixed by taking into account that:

- Typical limits on voltage variations in a centralised grid are 10 % in comparison to a 230 V nominal supply voltage. A decentralised source should not excess 2 % of the voltage variation.

- Typical limits on permissible frequency variations are 1 % for large grid. For small grids with less connected electric devices such as motors, the variations could be a little higher, and the diesel generators are responsible for frequency variations: the frequency is around 52 Hz when the diesel are operating are very low load, i.e. switching on, and around 48 Hz when they are running at full load.

Usually the voltage derivations do not exceed 3 %, because the diesel station is able to provide enough reactive power and ensure a good voltage regulation (see “Diesel Engines” paragraph). The most significant variations (corresponding to more than 3 % of voltage drops during 0.2 seconds) mainly occur during events such as start-up and shut down of diesel generators, large motors or wind turbines connected to the network.

In order to predict possible variations of these parameters it is necessary to study the steady-state and dynamic behaviour of the system as it was presented by the Brazilian Wind Energy Center [8] in the aim to increase the wind penetration in a WD system. The steady-state corresponds to low and slow voltage and frequency deviations during normal operation. The dynamic behaviour corresponds to voltage and frequency significant oscillations, provoked by a change of the load or supplied power. This dynamic behaviour is difficult to be studied, but it should be analysed to design efficiently a controlled WD systems by ensuring a good power quality and stability in continuous operation, a good stability after disturbances in the power system (e.g. short circuit), and a smooth answer to voltage and frequency short period variations.

The last parameter to follow is the level of availability. It is directly depending on the power interruptions. This level should be as high as possible to make the whole system reliable. However, it should not be forgotten that an electricity supply cannot be made 100% reliable: an exceeding secure supply would require duplication or triplication of equipment (high level of redundancy), but that would results in an exceedingly high electricity costs.

2.1.4 Electrical Equipment

Devices and electrical equipment have to be chosen and calibrated in consideration of the possible troubles of power quality. Power electronics and additional devices, used for specific strategies, are used in order to reinforce the system and to prevent possible troubles. These troubles could therefore be avoided as much as possible in small stand-alone WD systems, with appropriate electrical and mechanical design.

In small isolated networks, the constancy of the voltage and frequency levels should be kept between acceptable limits as in large grids, even if the electrical requirements are not as strict as it is for large and central grids. For small hybrid systems with low wind penetration, the system can be designed on the simple and robust concept, with a minimum of power electronics and no supervisory controller. However, power electronics can have an important rule in the system stability for stand alone system with high wind penetration. Properly placed and combined they can ensure a good power quality [9], even if redundant equipment would be related to high investment costs. The main used power electronics, their function and characteristics, are presented below. Most of them are used for facilities indirect connection.

They should be assembled in safety substations and adequately earthing in order to ensure no risk during operation, according to the local regulation, which should be as closed as possible to the

European or American ones. They are good references even if they are probably too strict for most of the small isolated systems located in developing countries.

- ***Converters***

Variable speed wind turbines are often indirectly connected to the grid. Their electrical output has a variable frequency, which is corrected with a converter: the turbines electrical output power is transformed to DC and again to AC. A converter is composed of the combination of one or several inverter(s) (i.e. large transitors) and one rectifier. In addition to filters composed of inductances and capacitors, it enables to get an output power at the grid frequency [4].

As remark, asynchronous generators can be directly connected to the three-phase alternating current of the grid, because the grid is holding the machine and the current of the turbine electrical output is adjusted in order to match the grid characteristics. That is why, weak grids unlikely support more than 1 to 3 MW of wind power produced by asynchronous generators, due to the fact that this type of turbine acts like a motor during its start-up and needs reactive power from the grid [3].

- ***Transformers***

The generated three-phase alternating current is at a voltage level around 690 V. It is raised by a transformer to the local grid voltage level, between 11 and 33 kV.

Wind parks could be connected to a local grid directly or to a main substation of the network. However, local network already build were designed for load distribution but not for decentralised renewable source connection. The installed capacity of new generators should be inferior of the already installed capacity into the grid, and should not excess the limits fixed by the local electrical line. It means that only small generators can be connected to existing weak networks, without reinforcement of the grid locally, e.g. close to the wind park only, or generally.

Reinforce the network is therefore required in order to carry the fluctuating current from the wind turbine. In this purpose, transformers are used in order to enable transport of wind energy and load supply at a higher electricity level. As stated in the previous section concerning the “Controlled Parameters”, these high voltage networks are further reliable, since they are less sensitive to a fault. The availability of the wind park will also be improved.

- ***Controllers***

Programmable controllers, also called regulators, are required. They must be used in conjunction to each device acting as consumer or as producer of energy. These electronic controllers monitor actively the voltage and frequency of the alternating current before the grid connection, at the output of the concerned device. They also control constantly the purity of the sinusoidal waveform, the active and reactive power flow variations, and the availability of the system. They must be adapted and programmed according to the function of the device. That is why special controllers are needed for each strategy:

- Batteries charge controllers are really important in order to protect batteries from overcharging but also from deep discharge, since that can significantly damage the batteries. If the battery level falls below a certain level voltage the controller will cut the current to the loads, to prevent further discharge. This controller should be coupled to the diesel set-up controller and should be efficiently programmed in order to regulate charging and discharging rates and to enable an efficient control of diesel engines switching on and off.

- The dump load device needs as well a relevant controller, which should be also coupled to the diesel set-up controller.
- The main function of the turbine control system is to coordinate a safe system operation by preventing the turbine from over-speed and overheating. If the controlled parameters of the electrical output of a turbine drop out of certain limits within a fraction of second, the turbine will be automatically disconnect from the grid and stop itself immediately afterwards.
- The diesel engines controller should coordinate a safe system operation of the diesel generators, e.g. protect them from high power fluctuations or from overload. This controller (also called diesel engines governor) is able to keep the voltage and the frequency constant, because it is able to regulate the active and reactive power flows in the grid, by adapted its shaft rotational speed and power production of the generators.

Other important details will be given in the technical description of the respective components.

It is possible to include a central controller to the system in order to regulate further more together all energy supplies. This type of controller is destined to avoid high repercussion on each device and its respective controller. In small systems, there is in general no central controller. Most of the time, the control of the whole system is ensured by an adapted diesel engines controller, which is described in the part regarding “Diesel Engines”. The system of control could be reliable enough, if it is previously well programmed to act as a function of all other controllers output data, such as e.g. the level of batteries charge, the level of dumped energy.

2.2 Technical Characteristics of WD Systems Components

This part presents a technical description of the basis components of Wind Diesel Systems. These components are mainly the wind turbines and the diesel generators. For the diverse strategies of control, other equipment can be added, such as dump load devices and batteries banks.

The generators have specific power characteristics and specific optimal ranges of power generation, and all of the possible combinations of these components have specific operating constraints and benefit intermittences. It is therefore important to take into consideration the effect of each component on the system in order to assess the effect of their combination.

2.2.1 Wind Turbines

The number of turbines integrated into the system will vary in the study, since the wind penetration is the most important input parameter of the model elaborated for this thesis. By the way, the chosen turbine characteristics are exposed below and this choice is justified. For further information about turbine’s characteristics refer to “Wind Park Projects Development” report [1], writing at a previous stage of the thesis.

- ***Size of Turbine***

Due to the size of the grid of interest related to a low demand and voltage level, small wind turbines should be first considered. Moreover, for rural electrification, the requirement of installation facilities could be a limitation for the size of the chosen turbine, e.g. the need of a crane for erection results of an important extra cost. That is why small turbines with simple erection could be more interesting for WD systems applications, in spite of the fact that small Wind Turbines (WT) are significantly less produced than the larger. The effect of the turbine type and size choice is important to be considered since the results can vary significantly for different type and size of turbines. This effect will not be discussed since only one source of turbine power production data were used for this study, due to the difficulty to obtained 10-seconds data for the comparison of the time scales.

- ***Synchronous Generator***

The wind turbine generators are a little different from other generating ordinarily units due partially to the fact that they have to work with very fluctuating mechanical power (torque). The wind turbines generators are commonly asynchronous, called also induction generator.

However, the most favourable configuration for voltage and reactive power regulation is wind turbines with synchronous generators, not directly coupled to the grid. As remark, it will be assumed in this thesis that the used turbines have synchronous generators, although there are few producers of small turbines with a synchronous generator and if these turbines are therefore more expensive.

This type of generator has a higher efficiency, but also numerous advantages for small grid integration as it was shown in the previous electrical part: this type of generator does not need reactive power from the grid to start up (when the wind is rising and begin to create a shaft rotational energy) as that is the case with asynchronous generator.

- ***Yaw System***

The maximum yield from the wind resource can be reached thanks to the yaw system which controls and corrects the position of the turbine in comparison to the main wind direction. The yaw system is able to ensure the alignment of the rotor in the main wind direction. Then, the yaw braking system enables to keep the turbine fixed in this direction.

An assumption will be that the system is well functional in order to maximise the electrical output power. As remark, one control strategy which consists to use this direction angle in order to make vary the electrical output was already tested. However the control by the yaw system is not an appropriate solution, for larger WT than 1 kW with three rigid blades, since it provokes high rotor and turbine fatigue and varying stress which may ultimately damage the entire structure.

A idea at an early stage of the thesis was to recalculate electricity production from given wind data for another turbine type, such as stall or pitch optimised (see “Other Elements for WD Systems Regulation – Pitch Control” part), but the wind data given by the yaw system are too much influenced from the rotor rotation and thus not enough relevant for other turbines electrical output power calculations.

- ***Internal Controller***

An internal turbine controller is necessary in order to ensure a safe operation of the turbine. It checks many parameters, important for the good operation of the turbine, such as the main direction of wind and the corresponding wind speed, the electrical output power, the pitch blades angle, the generator temperature or the nacelle vibration. And then, the system controls the activation and deactivation of the different turbine components induced in the operation and the emergency switching off (required in order to protect the turbine from storm and overheating of the main mechanical and electrical components). It enables also a user interface.

Protection equipment is required to automatically disconnect the wind park when there is a problem on the grid to protect the wind park but also the WD system (the grid and other devices) when there is a fault in the wind park.

2.2.2 Diesel Engines

Diesel generators are characterised by two main operational limits (maximum and minimum loads), a compression ratio, the type of used fuel as input, the treatment of the exhaust gases, etc. These generators are synchronous and are rated in terms of VA output as the maximum possible apparent power that can be provided continuously without overheating. The apparent power that they provide is directly related to the frequency of the delivered current fixed by its rotational speed.

In common configuration a diesel set-up contains 2 or 3 engines of the same size due to power availability, maintenance and purchase simplicity reasons. The diesel generators should be ISO certified. The standard ISO 8528 has to be used as guideline for the choice of the right diesel genset type, and the standard ISO 3046 part 1 associated to the standard ISO 8528 fix requirements for different capacities, defined as:

- COP: Continuous Power gensets, running at 100% during an unlimited number of hours per year,
- PRP: Prime Power, allowed to run at 60 to 70% average rating within 24 hours,
- LTP: Auxiliary Power, running at 100% during 300 to 500 hours a year, used for emergency requirements.

The rated capacity for an identical diesel unit is increasing from COP towards LTP.

- ***Diesel Engines in WD Systems***

Normal operation conditions for diesel generators in WD systems are in a range of 40 to 90% of partial load. At lower partial loads diesel engines are emitting higher concentration of pollutants due to non-complete combustion (low temperature). The optimal operation range of the diesel gensets in terms of fuel efficiency and stress is at 80 to 90% of the rated power. The term of full-load corresponds to this optimal operation range. The term of overload, which will be used later on, corresponds to the fact that diesel genset could not provide enough power since they should operate at a load more than 100%. Diesel generators rated according to ISO 3046 and ISO 8528 can operate at 100% load without overheating or having other operational problems.

In WD systems it is necessary that the diesel power production can vary to be adapted to the instantaneous needs. The following general formula gives the relation from torque to power:

$$\text{Power} = \text{torque} * 2\pi * \text{rotational speed}$$

With
- Power (Watt)
- Torque (Nm), it is the moment applied to a circumferential point of the generator shaft, i.e. the force applied to this point multiply by the distance from this point to the shaft axe
- Rotational speed (rpm) of this circumferential point

This formula shows that the parameter which changes the output power is the force applied in the generator, i.e. the pressure of the flue-gas. The power is therefore influenced by the feeding of fuel of the genset.

A four stroke diesel generator can have different rotational speeds linked to the size of the engine, between less than 500 rpm and up to more than 1,500 rpm or even 3,000 rpm for the smallest engines. In most of the cases, the diesel genset is running at full load and at a constant rotational speed in order to meet the grid frequency prevailing in the respective grid, either 50 Hz or 60 Hz. The frequency provided by the diesel generator varies as a function of the grid frequency, translated by a rotational speed variation. However, only at the dynamic behaviour the effect of wind energy integration could be observed as fast acceleration and deceleration of diesel generator, since the frequency is not supposed to vary more than 3%.

- ***Size of the Diesel Set-Up***

The diesel genset's capacity should be high enough to meet the maximum load, i.e. although the genset will probably run at low partial load most of the time, it should have the capacity to serve the load when there is no wind, or when the wind park is unavailable.

While choosing the diesel genset's capacity, the power consumption of the auxiliary equipment (e.g. control system supply, cooling system, etc) should be considered for the determination of the genset's net capacity available for feeding into the grid.

Finally, the design should consider the safety and power availability requirement of the system, i.e. in case that one generator is out of order. However, due to the previous design requirement to meet the maximum of the load without wind, this condition is mainly respected (always more than two gensets). As remark, the model elaborated for the following confirm it: most of the times one diesel genset is off while the others are in operation. The highest safety requirement that could be chosen is that the set-up design has to ensure that only one diesel generator is able to cover the load alone, in case the others are in maintenance.

- ***Diesel Set-Up Controller***

A diesel genset should be managed by an efficient control system, which is composed of a speed governor and a voltage regulator (as explained in the electrical part), in order to keep the voltage and frequency constant respectively. This control system may disconnect the generators from the grid to protect them, in case of a fault on the grid.

A controller of the entire diesel set-up should be included in order to regulate the overall power output of the diesel generators by switching them off or on. The generators to be active or not, in respect to instantaneous wind penetration in the system, would be managed by this set-up controller according to some limiting partial loads values, which have to be previously determined. This partial load management to switch off or on the diesel gensets will be of first interest in this thesis.

This diesel set-up controller should be carefully programmed in order to not disconnect too easily the diesel generators in case that a large increase of the wind power appears, because this disconnection will have as effect to disconnect the grid if the wind decreases suddenly after (what is per definition observed during wind fluctuations). However, it is important that it reacts efficiently when it is needed, i.e. when the wind speed regime changes significantly, to avoid drastic damage on the generators.

Programmable controllers are the key of hybrid systems but their design and programming is critical: it has to be adjusted to each situation, to be optimised for higher performance in ongoing operation, and it is governed by expensive costs and producer secret.

Through an Active Load Sharing System, the control system can distribute to the diesel gensets the load variation in two different dispatch strategies: an unequal percentage defined previously or an equal percentage of the variation is distributed to the active generators. That is another main concern of diesel genset operation, since this stresses the diesel generators more or less equivalently.

A strategy could be to stress only one diesel while the others are not influenced by the load variation, and then to permute, at fixed chosen time interval, the stressed diesel generator with another diesel genset. This operation mode should be disregarded, since it bears more disadvantages than the load sharing operation mode, such as a high maintenance requirement (low maintenance time interval in order to permute them). In this thesis it will be assumed that the load variation is overtaken identically by all of the active diesel generators.

- ***Reaction Times***

It is important to know how fast a diesel genset is able to take over the load, in the cases that the diesel is off or is already running (with or without load). The respective times necessary for generators to react to a change of operation, referred as reaction times in the following, are important parameter for WD systems design. The reaction times are proportional to the capacity of the genset: the times are shorter for smaller generators.

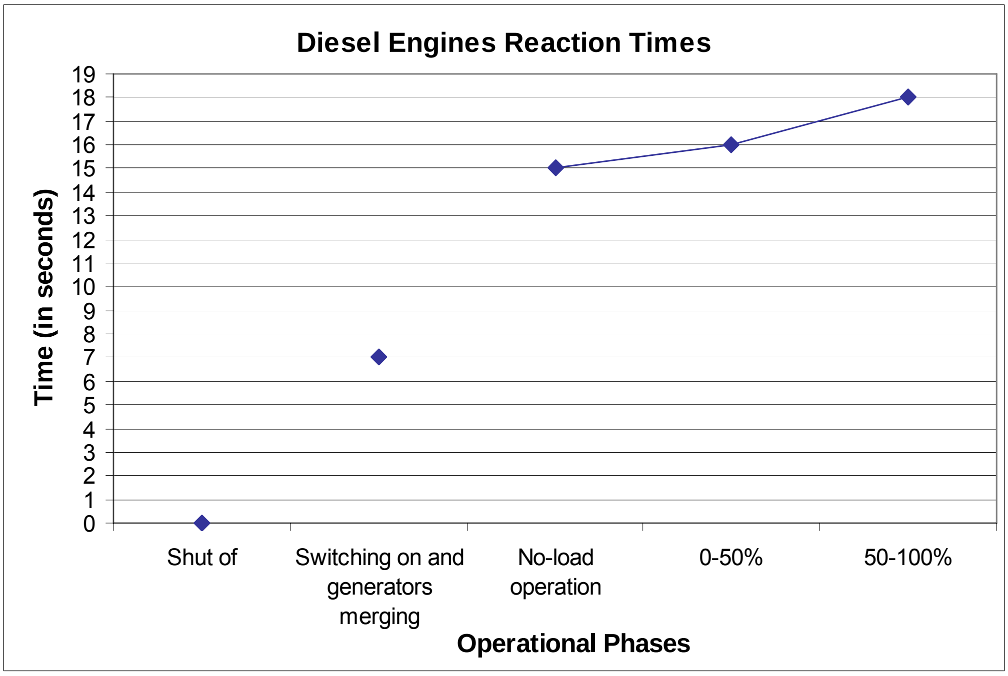


Figure 2-1: Diesel Engines Reaction Times during Switching On, Merging and Loading Regimes (Source: Caterpillar, Prime Power Diesel Engine, 2275 kVA, 50Hz, 3516B HD family)

As shown in the diagram above, the limiting reaction times are not the ones corresponding to load changes but to start-up. In case of instantaneous high wind penetration, it is recommended not to shut-down the diesel generators too early, because a drastic decrease of wind would result in a lack of diesel power during the first 15 seconds and power quality problems should occur. It will be shown later that this remark is particularly important when only one genset runs.

- ***Low Load Diesel***

Usual diesel gensets are designed to run efficiently at high load ratings, preferably at constant load. Low load running operation (less than 30-50%) with normal diesel generators results in exhaust gas particulate deposits, and fuel washed out into the lube oil, what increases maintenance costs.

Low load diesel generators are a new design of diesel generator system. Although they are more expensive, they can be an appropriate solution for WD systems, since the diesel gensets are idling at low partial loads for most of the operation time. They are able to run at low running percentage (25% to 40%) without damaging the genset and increasing significantly the emissions. This kind of diesel engine is important to ensure a base load and no significant frequency drop, but also to answer to rapid turbine output power change.

In addition to this new type of low load diesel many other types of diesel genset exist, such as generators able to overtake large load variations. The operation performance of each genset depends on the design of the machine (e.g. injection system, turbo charger, intake and exhaust gas path, etc).

- ***Maintenance Consideration***

The maintenance schedule should be carefully determined and observed. It should consider all the maintenance time intervals for all of the specific engines and for the entire system. Maintenance time intervals should be as long as possible in order to allow high availabilities of the units, and as much similar as possible in order to minimise the maintenance requirements, what is particularly important for systems in remote areas.

Diesel generators can manage drastic load variations but are consequently stressed, more or less, depending on amplitude of the voltage and frequency variations occurring during the dynamic behaviour of the system. Continuous high load variations increase the stress of the genset components and decrease therefore the maintenance time intervals. In general, in comparison with small diesel generators, large diesel generators can react faster to power fluctuations, maintenance intervals are shorter in time and fuel consumption and pollutants emission is smaller (in consideration that the load is proportional to the diesel rated power).

It is possible to consider the case to upgrade the diesel set-up and to reinforce the grid, i.e. install the new hybrid system with the gensets already used to supply this grid. However, in case of advanced age of the diesel gensets, it is mostly better to change the diesel generators with new ones, in order to make profit of the technology development, which enables an easier installation and programming and a better production, consumption and emitted pollution reduction.

- ***Exhaust gases and emissions***

Exhaust gas composition is a function of many factors. Among others are: the combustion temperature and injection timing (influence the NO_x concentration), the combustion chamber and piston design (CO_2), the fuel specification of gasoil (SO_x, particulate matter, others) and the specific fuel consumption (CO_2).

As remark, gasoil (i.e. Marine Diesel Oil or Heavy Fuel Oil) is often used as input for large generators (above 5 MW), and diesel (i.e. light fuel) is used for small diesel gensets (on the international market, diesel engine capacity is mainly under 1 MW).

At low load (less than 45 % of running percentage, the temperature is lower, the efficiency lower and the specific fuel consumption higher. The concentration of emitted pollutants, such as the particulate matters, is thus higher. Low emission and low specific fuel consumption versions of engines are available but are more costly.

2.2.3 Other Elements for WD Systems Regulation

In a central grid, the utility is in charge of the grid: manage the voltage and frequency stability, dump the excess power and fill gaps with utility power. A distributed source, such as wind turbines, can be integrated to the grid without major problem in developing countries or dense populated areas, since it represents in fact a very low penetration in the entire system. The integration of decentralised renewable sources at high penetration in isolated grids is therefore a challenge because of natural and unforeseeable fluctuations.

Several strategies are elaborated in order to control further more hybrid systems. They consist to add other equipment to carry out the possible instability of the power. They are based on the principles that excess of energy can be lost, store or regulated.

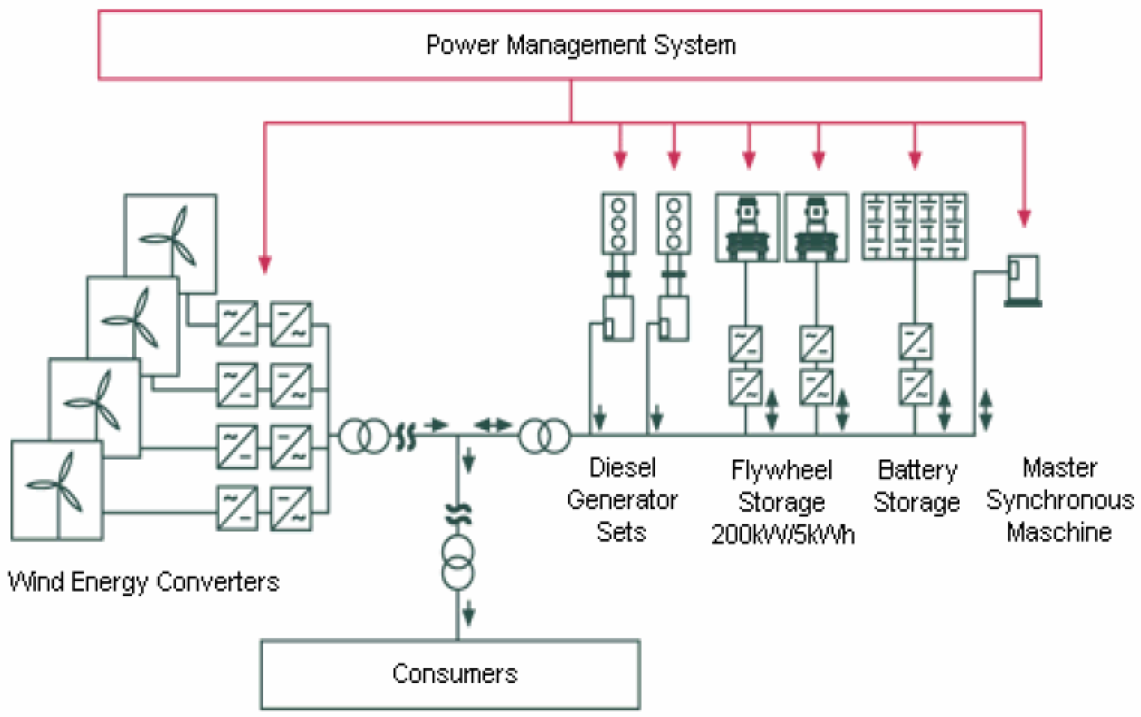


Figure 2-2: Necessary Components of Stand Alone Wind Diesel Systems (Source: “Wind Diesel and Stand Alone Systems – Products and Services”, ENERCON)

The low load diesel strategy is one of the most promising solutions for efficient control of WD systems. This was presented in “Diesel Engines” part, and will be further developed in the methodology.

- ***Dump Load***

The dump load devices are used to avoid excess of energy in the grid. This excess, which have to be dumped, is referred as the rejected energy because it is not used even it is produced. Rejected energy in WD systems is mainly due to excess of wind power. It can also be produced by the diesel generators if they are forced to run at higher partial loads than they should. This strategy is explained few paragraphs below.

These devices are specified by their rated power. They operate at lower power of this rated power without overstressing the material and damage it. The manufacturing units are operating in general under 24 kV. However, higher voltages off 36 kV, are currently implemented. Compact resistors element made of high-resistive material grids (such as stainless steel) fixed to load-bearing bolts and insulators, are used in order to dissipate the energy. The resistive load banks size vary between 1 and 25 ohms. Resistive load directly influences the flow of dumped power, i.e. the amount of energy and the time required to reject it. The resistor should be equipped with a circuit breaker and a disconnector, and this equipment should be adequately grounded in a safe place.

A dump load unit should be carefully designed regarding the required power consumption but also the local ambient air conditions, which are mainly the temperature and movement. Air movement can be created around the resistor with a ventilator, which could consume of portion of the rejected energy. Additional cooling can also be used in order to implement the flux of rejected energy. Such dump load device has therefore a lower efficiency and potential in hot countries in consideration that all the reference operating values are estimated for an ambient air temperature of 20°C. It is possible to install the dump load device in underground local to try to decrease the ambient room temperature.

Small dump load units are usually added to turbines or electrical systems in order to dissipate possible excess of electricity and to improve the degree of safety. The first aim of dump load equipment in WD systems is therefore to protect the system from overload, but it could be used in the aim to maximise the wind penetration. High amount of excess energy should be avoided as much as possible, but an acceptable amount of rejected energy could be determined.

The design of a dump load unit should be focused on an appropriate size related to the rated power and on a suitable controller, which should respond fast to voltage variations and which could be coupled to the diesel set-up controller. With a sensitive and calibrated measurement equipment, the quantity of dumped energy could be used as input in the diesel set-up controller as criteria to switch on and off the gensets. With a correctly monitored dump load device (based on sensitive measurements of the grid voltage), it should be thus possible to determine a limiting quantity of rejected energy to switch on again one of the diesel generator, in the consideration that a diesel genset needs a specific time to be available to operate (see "Diesel Engines – Reaction Times" part).

Another strategy using dump load, is to force the diesel generators to produce more that they should, and dump the excess when it is not needed, but use this excess when it is needed to respond to fast wind fluctuations. That could decrease the influence of wind penetration on the diesel generators operation. In this consideration, the diesel generators could be forced to operate at fixed constant levels (above that they should produced) as a function of the levels of produced wind power, and the excess would be dumped or used depending on the wind fluctuations. However, even if it could be an efficient strategy to be developed, no documentation about this was found.

Finally, if high amount of rejected energy should be dumped, management strategies should be considered. As stated in the part “Isolated Grids Characteristics”, the main strategy is the demand management with the repartition of the needs during the day.

The management of the rejected energy consists to use the excess of energy, when it is produced, for other applications such as water supply: with a geologic relief enough important around the considered remote area, the slope can be used in order to pump water in storage tanks (at higher altitudes than the village altitude), during excess of energy, and to supply the area with a pressurised water distribution system, the rest of the day (with enough excess of energy in comparison to local tap water demand). It is also possible to add a hydro power turbine in order to produce energy while the water goes from one high altitude to a lower (the greater is the slope gradient, the higher could be the electrical production). This solution is therefore similar to energy savings, but losses of energy are higher and the impact on the cost of energy seems to be too much important to justify this double strategy with the installation of a micro hydro turbine.

However, these strategies concern the accessibility to both water and energy resources, and this is related to urbanism development. Such strategies could be thus difficult to be developed, even if the use of excess of energy can participate to develop the standards of living in remotes areas.

- ***Energy Storage***

Battery storage is realised by electrochemical reactions. The energy is stored or released depending on the direction of the reaction appearing in the battery. This reaction varies as a function of the electrolyte (composition, concentrations, reaction rates) and electrodes (number and sizes of anode and cathode plates).

The main criteria for battery choice are its capacity and its rates of charge and discharge. The discharge or charge current in amperes that could be operated during a certain period is commonly expressed in Ampere-hours (Ah). The rates of charging or discharging depend on the internal resistance of the battery, both rates are not similar, and these depend on the battery type, the applied voltage but also the level of charge. The batteries ability to store and deliver energy could be expressed in kWh, as the product (divided by 1,000) of the rated capacity in Ampere-hour and the nominal battery voltage. It depends on the area and the technology of the battery plates, but also of the chosen configuration of the battery bank.

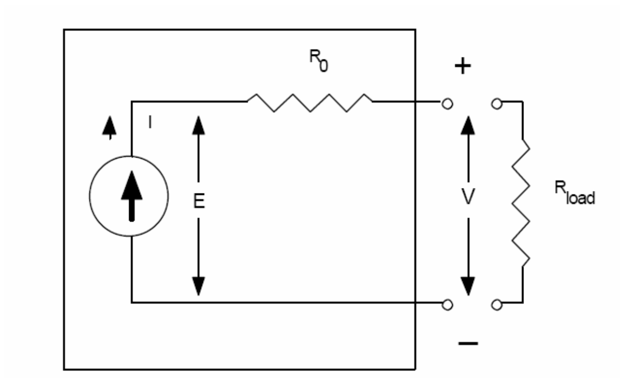


Figure 2-3: Simple Battery Model Equivalent Circuit
(Source: “Improvements to the Hybrid2 Battery Model”, American Wind Energy Association, Windpower 2005 Conference)

Corresponding controller, transformer and inverters should be installed in order to match the voltage of the batteries to the voltage of the grid. Common operating voltages of the batteries are 6, 12 and 24V. The compilation of batteries, in parallel or series, has the effect to influence the voltage and current levels applied to the batteries. The figures 2-4 represent the typical profiles of the voltage (left) and the current (right) of batteries during charging time.

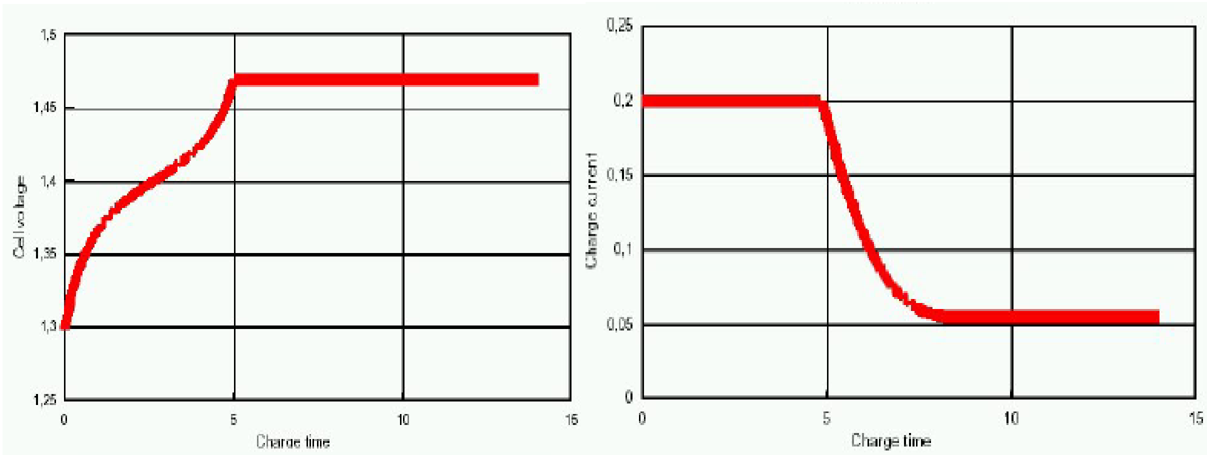


Figure 2-4: Voltage and Current Charge typical Curves (Source: "Battery Guide for Lead-Acid and Ni-Cd Batteries in Stationary Applications", Saft Company, 13/06/2004)

The batteries should be assembled in an easy access, clean, dry and ventilated enclosure at moderate temperature and protected from over-current protected and again acid spills. An appropriate controller is required to charge the battery when it is possible and to discharge it when it is required, as example, the controller includes an automatic charge control regulator to prevent battery from overcharging damage. This controller should operate in response to the diesel set-up operation and the network characteristics.

When a low current for long periods is required, deep cycle batteries can be used. In this case, the capacity is the important parameter, as the amount of current that can be drawn from the battery continuously. Deep-cycle batteries are designed to operate over large range of voltage levels. This type of batteries can discharge to 70-80% without damage (other batteries are only designed for low percentage of discharge).

When high current for short periods is required, batteries with a high ability to deliver instantaneous current can be used. It is referred as the maximum rate of discharge, and is therefore one of the most important criteria for short term power storage in order to control wind and load fluctuations that can affect WD systems.

This is also known as Cold Crancking Amps for diesel engines starting. Adequate crancking currents should be defined as a function of the diesel genset set-up: most of the times engine manufacturers specify the minimum CCA of the battery required to start their engine. Generally the required crancking current is very high, and that is why special batteries are used for this purpose, in addition to eventual batteries for energy or power storage (long or short term, see following paragraphs).

Lead-Acid and Nickel-Cadmium batteries are currently the most used, while Nickel-Metal Hybride and Lithium-Ion batteries emerged. The Lead-Acid and Nickel-Cadmium batteries have well differentiated characteristics. The advantages and disadvantages of both types are compared in the appendix 3.

Lead-Acid batteries are deep cycle batteries, and they are sized to provide several days of electricity in stand-alone systems. As example, it is possible to reach a ranging capacity from 20 to 100 Ampere-Hours (Ah) with this kind of battery. Nickel-Cadmium batteries have a low intern resistance, they have several advantages compared to the lead-acid type: they discharge at faster rates, they have higher designed life time, good operation even at high temperature, short recharge time, no problem with deep chare, simple maintenance. However, the initial costs of NiCd battery and charger are also higher, and moreover this kind of battery is harmful for the environment. Their usage is forbidden in Sweden for this reason.

The different strategies for batteries usage in hybrid systems are related to the wish to use the batteries to save as much as possible renewable energy, or just enough energy in order to control WD systems and to prevent it from wind fluctuations effect:

- ***Long Term Storage***: it is the storage of bulk energy over long time period, in order to save as much as possible renewable energy when it is available but not needed. There are several saving strategies: the energy is saved during the day and used the night, or the energy is stored for several days without renewable energy. Lead-Acid batteries are the most appropriate this application. However, it is difficult to store power electricity over very long periods because of the energetic losses (i.e. the battery self-discharge due to reversible electrochemical equilibrium).
- ***Short Term Storage***: it is the saving of power, since it delivers high quantity of electricity in a short time. The size of the battery should be just enough to enable a good system control, i.e to provide power during wind fluctuations and diesel gensets switching on. The aim is switch off the diesel generators as much as possible and to favours a smooth relationship between wind power and diesel generators power productions. The cadmium based batteries are the more appropriate with a high capacity inverter.

As remark, there are other types of short term power storage technologies, such as the flywheels, or the super-capacitors. Flywheel is a promising technology. Low speed flywheels with steel rotors are suitable to store limited energy quantity during 10 to 15 seconds. High speed flywheels with composite rotors should save higher amount of energy but they are not actively developed, widely used and therefore expensive. Super-capacitors can save or deliver limited amount of energy during short times (e.g. 30 seconds). It is a good power option due to their characteristics: high cycling capacity, high rate charging, no effect of the temperature on wide operating ranges, and no need of maintenance.

Stress factors are important to be considered for battery storage system design. They are related to damage mechanisms, which affect the performance of a battery. The level of damage depends of the design, selection of materials, manufacturing processes, and the local conditions. As example, the temperature can have an important effect on batteries operation and their lifetime. Lower temperatures than 20°C decrease battery capacity, and higher temperatures increase the capacity but reduce significantly the lifetime of the battery [5]. An ambient temperature of 30°C ambient limit during 24h corresponds to very high operating conditions for batteries. Lad-antimony batteries resist more to higher temperatures. The grids of these batteries limit the shedding and self-discharge of the battery and these have better life time than others at higher temperatures.

The depth of discharge has also an important impact on the cycle life, as shown the curve below for gel cell lead-acid battery: 200 cycles for discharges of 100 % of depth and 5,400 with only 30 % of depth [5].

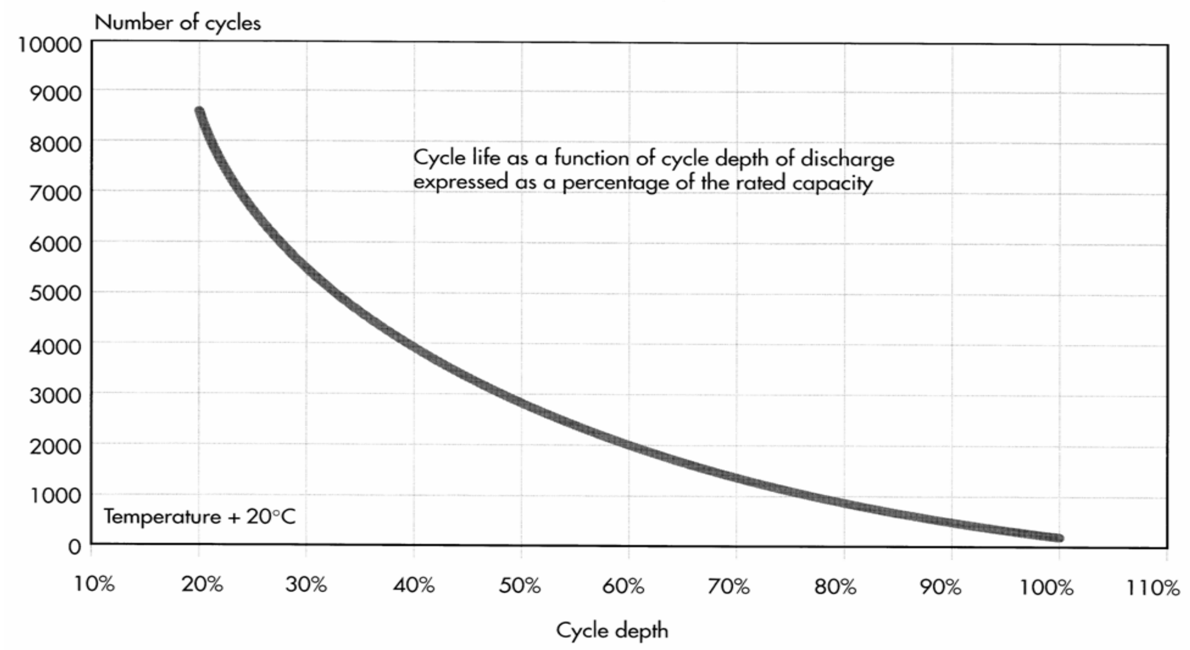


Figure 2-5: Number of Cycles vs. Depth of Cycle Discharge (Source: Saft, the Sunica System using Nickel-Cadmium Battery, Presentation at Lahmeyer, 20/01/2004)

The diverse damage mechanisms are: corrosion of the grid, shedding, water loss (or drying out), active mass degradation and electrolyte degradation. In appendix 2 a cross matrix of the stress factors and damage mechanisms is given. These could influence significantly and the theoretical battery lifetime. Battery lifetime depends on numerous of design and operational factors such as the components and materials of the battery, temperature, frequency and depth of discharges, charging methods linked to the used controller, cut-off voltage, and memory effect of the battery.

The batteries have in general a low life time in comparison to diesel gensets or wind turbines. It is from 3 to 5 year for common simple batteries used for long term storage, more for deep-cycle batteries, and up to 20 years for nickel-cadmium type. Quantify the lifetime of battery within a system is difficult, it is often a limiting parameter due to regular investment requirement.

Moreover, it is difficult to design a system including batteries that ensures a long battery lifetime and a high reliability. Moreover, the limitations for transportation and maintenance in remote sites are other barriers in addition to the high costs for investment and the short lifetimes. In order to give an idea about the prices, Merlin Equipment Company provided the cost of a battery for engine starting: 125.95 $/unit (characteristics of this battery, called Odyssey: dimensions of 200*169*172 = L*W*H, nominal voltage of 12 V, capacity of 44 Ah, discharging current of 860 Amps during 30 seconds at 20°C (725 Amps at 0°C) and a high CCA of 1,200 Amps during 5 seconds).

The design of WD systems based on energy storage has therefore a limited technical challenge, but design the battery bank in order to optimise the control of the system is of another importance. Short discharge times, fast charging and controlled discharge rates are the optimised performances of battery that should be used for control purpose in response of high power storage requirement.

- ***Pitch Control***

There are many types of passive or active controlled turbines linked to their technology. Passive stall and active pitch control consist to influence the electrical output of the turbine. The principle is to dump directly at the source a part of wind energy before its integration into the grid, and decrease in the same time the fluctuation of the electrical output. That is particularly relevant when the load of electricity is too high, i.e. when the excess of wind power cannot be integrated into the grid and should be directly dumped.

Stall turbines dump the energy at high wind speeds with a special design of the blades, which creates turbulences after the blades at a certain wind speed level and limits thus the electricity output produced by the generator. This kind of passive control is often used to protect the rotor from over-loading or over-speeding.

Pitch system is an active control system included in the turbine rotor. The first goal of the pitch control system is to protect the turbine from overspeed of the rotor. Active pitch control dump a part of the wind production, or can optimise this production at lower wind speeds: when the power output becomes too high, the rotor blades can be pitched (turned) slightly out of the wind is wind rise appear, and reversibly the blades can be turned back into the wind in case of the wind drop. The pitch mechanism is usually achieved by hydraulics. It is controlled by intern pitch turbine controller, which accesses the optimal pitch angle from the electrical output. The rotor blades orientation angle (called pitch angle) influences the rotor velocity and then the electrical output: with a blade rotation around the longitudinal axis, the flow through the blades can be laminar, what optimises the electrical output, and it can be turbulent in order to break the airflow over the blade and reduce or avoid excess of wind energy production.

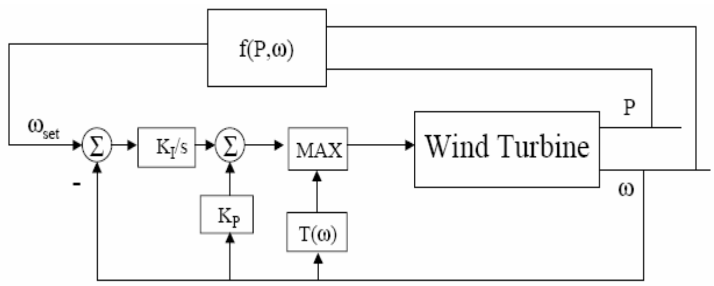


Figure 2-6: Schematic Bloc Diagram of Active Pitch Control System (Source: "Maximizing Energy Capture of Fixed-Pitch Variable-Speed WT", Kirk G. Pierce & Paul G. Migliore, NREL, Conference Paper, July 2000)

Variable speed turbines and non-variable types are linked to the generator operation. Non-variable turbines can be directly connected on large grids due to the relative constancy of the electricity output and the high level of fault in these grids. Variable speed turbines should be indirectly connected to the grid as in WD systems since their output frequency vary. Variable speed wind turbines use the inertia of the rotor and thus regulate the electrical output by avoiding significant fluctuations. This pitch controlled variable speed turbines can constitute a promising development of WD systems in the condition that they should be further optimised and well integrated. In theory, the optimised pitch control can ensure an acceptable level of wind power production, and therefore good operation conditions for diesel generators, but rapid response and precise prediction of the electrical output control system are still at an early stage of development. The design of pitch controlled wind turbines requires relevant engineering to make correspond adequately rotor blades pitch angle to turbine's electricity output. A thesis research done in Western Australia [6] has shown the possibility to optimise the electrical output by the efficient combination of pitch control system and converter/inverter transformation. Variable speed wind turbines with pitch control system can therefore be used in order to optimise the output voltage and frequency, and decrease the effect of wind fluctuations on WD systems. As remark, pitch controlled non-variable speed wind turbines are linked to high fluctuations of the electrical output and are not anymore sold.

- ***Strategies Combination***

WD systems components are compiled in order to obtain reliable system as a function of the local requirements. They are further more used to control the system. Highly controlled systems are possible but expensive, due to redundancy of equipment. The currently installed systems have many technical facilities, and are therefore linked to high costs of energy. The combination of wind, diesel generators, batteries and dump load device is common of usage: dump load is most of the times added to WD systems to ensure a better degree of safety, like short term energy storage reduces the effect of wind fluctuations, which responds to WD system control requirements but brings significant costs. Increase the number of component in the system, increase its reliability, but increase the system complexity, the investment costs.

However, studies about renewable energies in hybrid systems show the interest to diversify these energies. The combinations are most of the times more cost-effective than one of the technologies alone. The following chart presents a synthesis of hybrid systems cost-efficiency, with the wind abundance versus the daily load requirement.

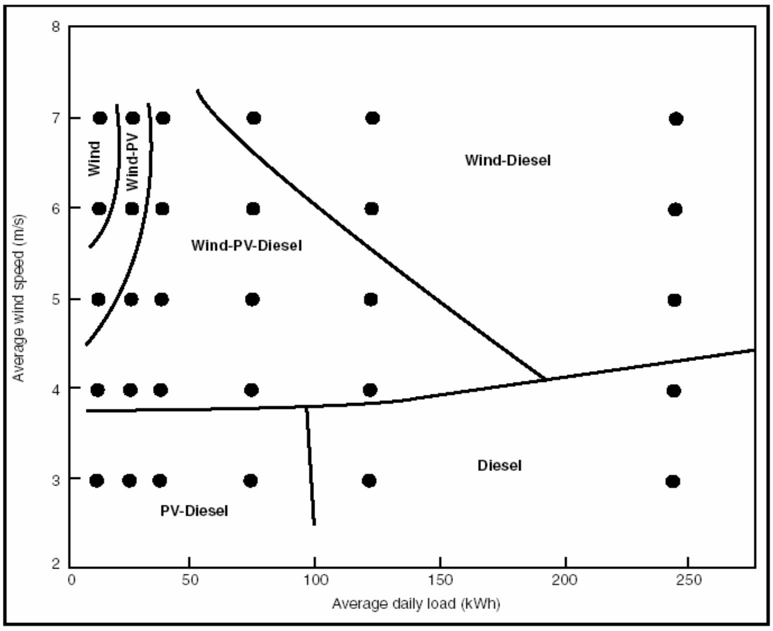


Figure 2-7: Hybrid Systems Optimisation Model for Renewable Energies, determined with Homer Simulations (Source: the National Renewable Energy Laboratory, 1999)

The challenge of WD systems is to find simple but robust systems with a limited cost of energy. In this thesis, only the combination of low load diesel and dump load device will be considered since the aim is to study the effect of wind fluctuations on the stability of the system, and the possibility to further develop WD systems with very small battery bank or without battery usage.

3 METHODOLOGY

The challenge is to adjust the power supply according to the demand with sufficient power quality and making effective use of the available wind energy. The methodology of the assessment of the wind penetration, rejected energy and diesel reaction is presented in this part. This assessment will be focused on the comparison between the situation with a traditional system, supplied by diesel generators only, and the upgraded situation of the wind energy system.

For this assessment two different models were developed: one for wind data interpolation and another for hybrid system evaluation. The input data for the second model will be the output from the first. That is why, the results for the first wind data estimation are presented in this methodology part and not in the results since there are part of the preparation of the main programme. The aim of the first estimation is to process the wind data in order to figure out the effect of extra turbines (see just below) on power production. At the same time it will allow to make the number and capacity of wind turbines vary in the second model and then to study how high can be the penetration without compromising an efficient control of the whole hybrid system.

Another aim of this part is to figure out the critical operation conditions of the complete system. The three distinct time scales (hourly, 10-minutes and 10-seconds) will be used and this should enable a detailed analysis of these critical conditions. Another interesting result of this research would be to define the keys destined to check power quality and to correct this first design of WD systems if major electrical problems are observed.

3.1 Wind Data Processing

The objective of this part is to present the input wind data, how they were found, used and processed for further WD systems modelling.

- ***First Analysis of the Used Data***

A first analysis of the provided wind data is necessary. This data concerned mainly the wind speed measured at the yaw system and the produced wind power, i.e. the electrical output, of several WT. These data sets were provided by the company GE-Wind. There are coming directly from the data acquisition system of three turbines of 1.5 MW rated power localised in Germany.

The sets of the data used in this thesis are composed of 10-minutes and 10-seconds average data. This was recorded in consideration of the requirements for this study. In general 10-seconds values are not available since they are used for 10-minutes average data calculation and then they are deleted due to limited saving capacity. The given raw data will not be correlated or interpolated since the control system would have to be based directly on this type of data, whenever there is an error or not of the data acquisition system.

The time interval common for the three turbines is 8 days, 6 hours and 40 minutes for the 10-minutes data, and 8 hours and 43 minutes for the 10-seconds data. Important information about this data is that there are not really representative since the turbines are not working at rated power in any time of the provided wind data. Unfortunately at a previous stage of this project, only this data was available, and the study was based on this data and not longer time period, since the precise estimation of extra turbines requires time resource. Whenever, the model can be used later on with other data sources in order to have longer time intervals.

- ***Time-Scale Influence***

Wind variation over different time scales: inter-annual changes, seasonal variations, short term variations caused by/linked to wind turbulence. The short term variation makes the modelling particularly difficult because these fluctuations are amplified by a non linear response of the wind turbine: output power of wind turbines varies second by second depending on the strength of the turbulence. As remark the tower has an effect on the electrical output when the blades in their rotation past in proximity to the tower, but the non-homogeneity of the wind speeds over the rotor area is more important than the effect of the tower.

The effect of the time base of the data is therefore important. This effect is clearly shown in the graph below. 10-minutes based data is not taking into account the fluctuations of the wind, which are by definition the wind variations in the scale of less than 10-minutes. The 10-seconds data is more representative of these wind fluctuations even if the second variation can be expected even more significant. As remark, it can be seen that minute average data is already more representative of the wind comportment than 10-minutes averages. The control system could maybe be based on minute averages and not necessary on 10-seconds data. The study will therefore bring an idea of the necessary time base to use for the control system.

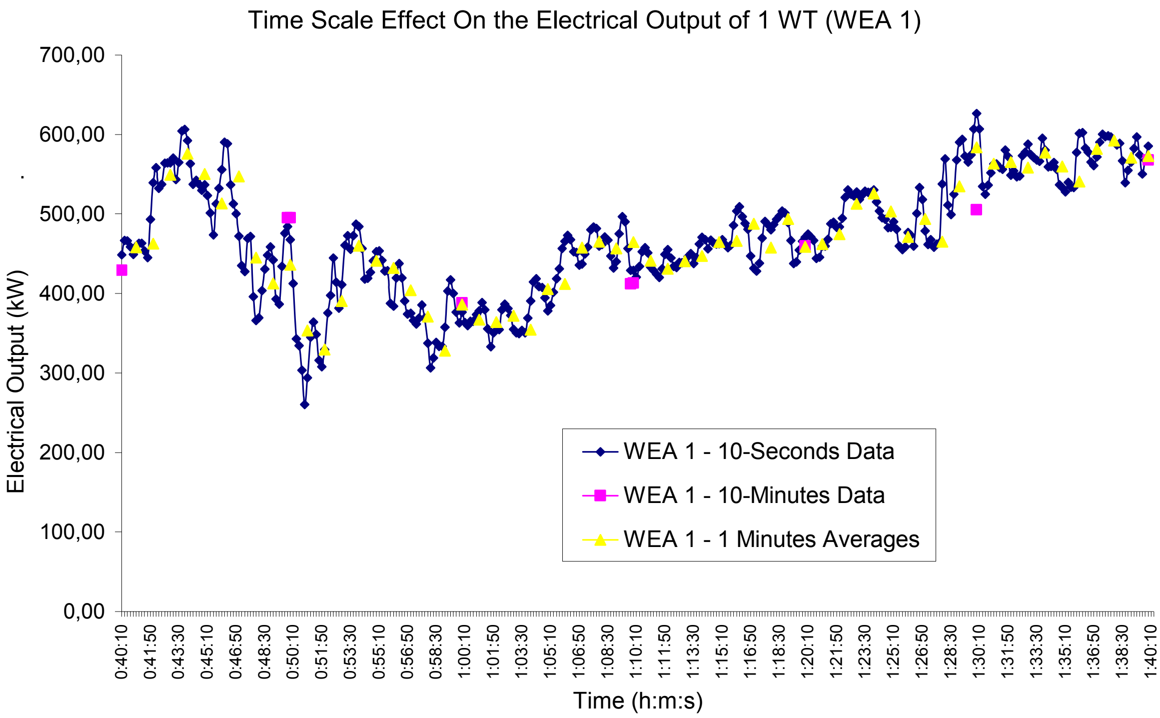


Figure 3-1: Effect of the Time Scale on the Precision of the Electrical Output of one WT

- ***Extra Turbines Modelling***

The data provided for 3 turbines allows a good modelling of other virtual turbines necessary to study the effect of wind penetration on WD systems. The wind penetration is directly linked to the number of turbines for a given load level. The effect of turbines grouping will not be directly studied in this thesis, but it would be considered. This effect of grouping is related to the use of several smaller turbines rather than one or two large. The grouping of turbines has the effect to decrease the fluctuations of the total generated wind power, while fluctuations of the output power from one turbine might be important. This effect could be obtained within one large wind park or several wind parks: the diversity of locations will ensure a diversity of instantaneous electrical output power (level and fluctuations) and should decrease the fluctuations of the overall generated wind power. A smoother power output from the wind generators could therefore be expected.

From the three first WT, three or six virtual turbines were modelled. This will allow to vary the number of turbines in the model from 1 to 9, what corresponds for the defined type and size of the turbines to an installed capacity varying between 1.5 and 13.5 MW.

The extra virtual turbines were placed at 500 m and 1,000 m from the first ones in the main direction of the wind. This distance is often used as a good condition to fulfil the requirement of micrositing (refer to “Wind Park Projects Development” report [1] for details about micrositing and this assumption).

The time necessary for the wind to go from one turbine to the next one is thus the distance divided by the velocity. For each value a postponed time is obtained. Then the electrical production at virtual turbines can be estimated as the value at the real turbine, with a delay corresponding to this postponed time. Clearly:

P (virtual turbine, t = 0) = P (real turbine, t = - postponed time= - distance/(velocity at t=0))

The calculation of this postponed time for each time value gives results varying from one minute to another. Thus, the modelling requires a minute estimation of the values. This minute estimation was done with the approach that the variation between two 10-minutes values is linear.

For 10-minutes data analysis, a rough estimation by multiplying the production of each turbine by 2 or 3 in order to get the overall production of 6 or 9 turbines was considered as admissible. This estimation is justified by the fact that the values of the required time vary mainly between 1.5 and 5.5 minutes with 72 % of the calculated time between 2 and 3 minutes. The effect of this shift of 2 minutes in comparison to 10-minutes values can be considered small, and that is why this estimation is relevant.

For 10-seconds data analysis, a postponed time of 70 seconds has a greater effect on this extra turbines modelling. Therefore, in the will to ensure reliable and representative data, the values were adjusted by more appropriated postponed time as described before this possible estimation.

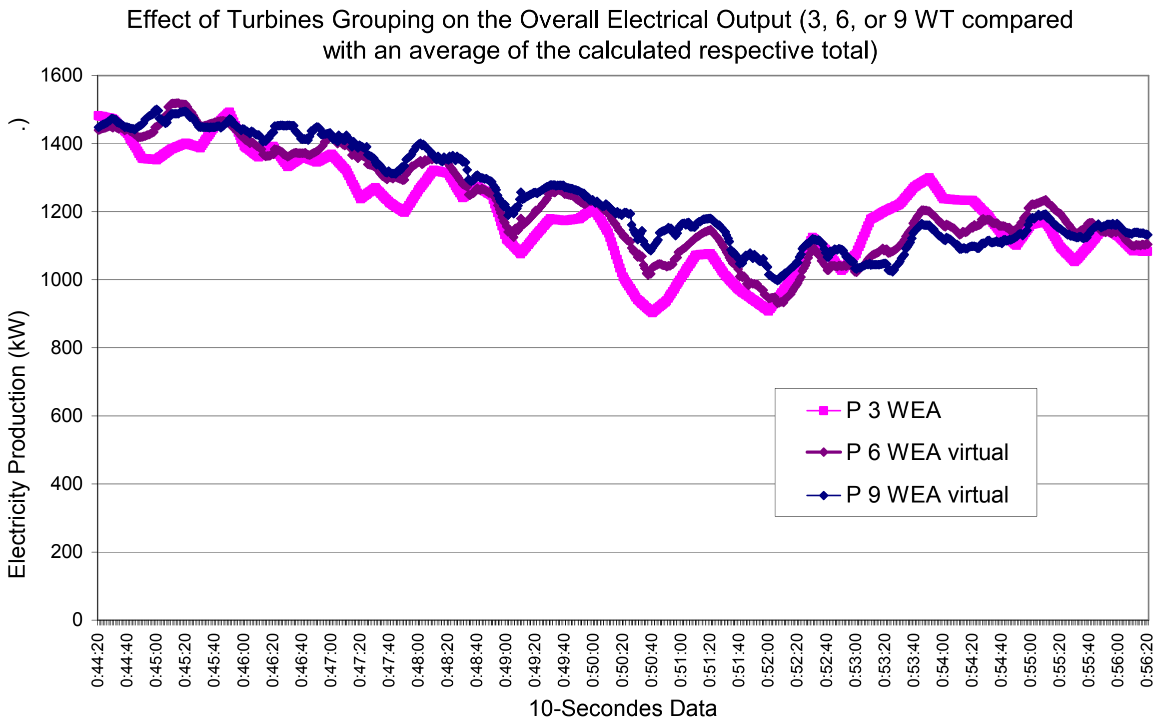


Figure 3-2 : Modelled Effect of Extra Virtual Turbines on the Electrical Output Power, 10-Seconds Data over 12 Minutes

As remark, the figure above is given in methodology part and not in results part since that will be used as input for the results. This figure shows that a drastic change of the wind will not result to a smoother electrical output while the wind regime is changing (the virtual curves should be multiplies by 2 or 3), but result in a smaller wind fluctuations effect. The effect of power grid fluctuations with a single or small group of turbines will be therefore even more important than for a combination of many turbines. As remark, it is important to remember that this curve was plotted with a restrictive assumption, i.e. the virtual turbines are placed at a fixed distance from the real ones. The input data is much reduced in order to study relevantly the effect of grouping in this thesis. The effect of grouping with diversified wind turbines and locations will have however a greater smoothing effect.

- ***Year Estimation***

Based on the provided data, the Weibull factors can be determined by Wind PRO processing (see the previously written report [1] for details about Wind PRO and the Weibull distribution, plot and usage). That enables to have an idea about the real wind potential on the site during a typical year.

The estimation of the Weibull distribution is particularly important in the aim of figuring out the saving on a year. This estimation is made in order to have significant and comparable results. In this thesis context, the determination of these Weibull factors by Wind PRO does not give highly accurate results since the data used for Weibull factors calculation was based on a short timeframe (approximately 8 days). In general it is done on minimum few months. These factors are given below, just as information. They will be not used since the aim of the thesis is not to determine precisely the possible savings of WD systems.

Table 3-1: Average Wind Speed and Weibull Factors Estimation, corresponding to the given 10-Minutes Data

Average Wind Speed (m/s)	5,603
A-factor	6,235
k-factor	3,418

3.2 Load Simulation

Most of the study presented in the following is based on a constant load in order to follow mainly the variation of the system due to the wind fluctuations. However, it would be interesting to compare the results obtained for the constant load with the ones for a typical daily variable load.

The load used as reference for this purpose remains from a WD system feasibility study achieved by Lahmeyer for a small village in a remote area in Africa. This data was measured every hour during one entire year. That enables to use the monthly averages of the daily curve in order to calculate the year average of the corresponding demand. This average daily demand will be used in the thesis as a typical daily variable load. It is more important to use typical data, which reflects the reality, and not necessary precise data as for a real feasibility study.

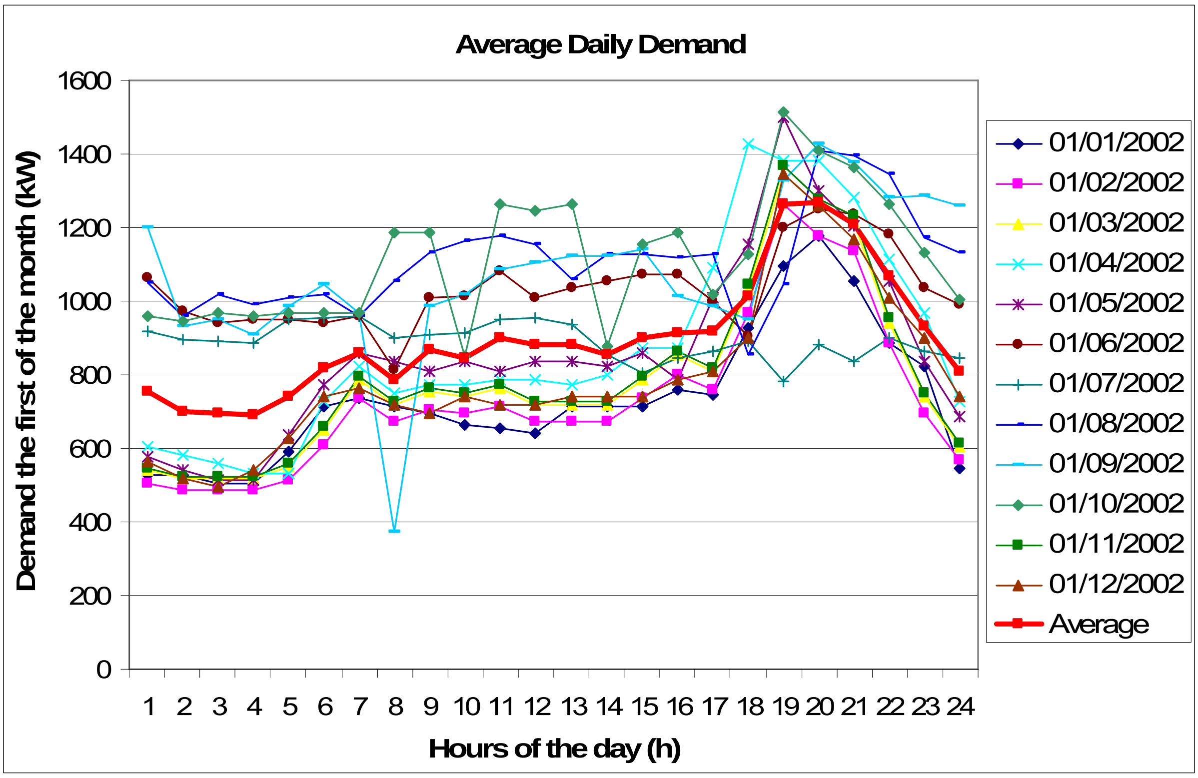


Figure 3-3: Average Daily Demand based on the Demand every First of the Month during a Year (Source: Lahmeyer Data measured for WD Systems Design)

3.3 Modelling of WD Systems Characteristics

The characteristics of WD systems are mainly corresponding to the power balance. They will be followed through the wind penetration, the amount of rejected energy and the amount of power to be produced by the diesel generators. The resulting power quality in a WD system will be followed through the study of the diesel set-up operation.

3.3.1 Wind Penetration and Rejected Energy

Wind Diesel Systems face some limitations related to the increase in wind penetration: systems with low penetration are commonly developed, while systems with high wind penetration represent a challenge for optimisation. The aim of this part is to study the way the WD system reacts to small time scale variation of the wind production, and how the wind penetration can be increased while ensuring reliable supply of good quality power.

The penetration is defined as the proportion of electricity produced by renewable sources compared to the total required electricity. The wind penetration could be expressed in two different ways: the average and the instantaneous penetration. The first is referred to energy yields and the second to power capacities:

Average Penetration = Wind Energy / Total Consumed Energy
Instantaneous Penetration = Used Wind Power / Load to be Provided
= Used Wind Power / (Used Wind Power + Diesel Power)

The difference between both penetration values, average and instantaneous, can be very significant since the energy produced by the wind turbines highly varies with turbulences. The maximum penetration is determined by the instantaneous value, thus it corresponds to the sum of the rated power of the turbines divided by the sum of the rated power of all the technologies included to the mix (diesel generators added to the turbines).

Instantaneous wind penetration values for each time scale were calculated. Then these were used for average values calculation and comparisons. For further purposes, such as the design of an active system of control, the instantaneous wind penetration should be considered.

When the instantaneous wind penetration is high (e.g. low load, efficient wind production), an excessive production of electricity may occur. This excess produced by the wind but not needed, which corresponds to rejected energy, must be dumped in order not to destabilize the network. As it was stated in the previous part, high amount of excess energy should be avoided as much as possible, but acceptable amount of rejected energy could be defined as a limit and set-up in the model.

The challenge is therefore to **maximize the wind penetration and to minimize the rejected energy**. An optimum shall be determined by coupling the two curves of these respective parameters, and the curves resulting from the following diesel reaction analysis.

The relations between the wind penetration, the rejected energy and the power to be produced by the diesel set-up could be expressed as a function of the wind production (depending directly on the number of turbines) and the load. These relations can be obtained from the following power balance, which can be applied to all systems:

Input + Accumulation = Output + Excess

For a Wind Diesel System, the "Input" comes from the wind turbines and the diesel generators, there is no accumulation, and the equation gives:

Wind P + Diesel P = Load + Rejected Energy

Or Load = Wind P + Diesel P – Rejected Energy

From this balance, the wind penetration can be expressed in percentage of the load as:

Wind Penetration = Used Wind P / Load

With Used Wind P = Wind P – Rejected Energy

Then the rejected energy can be defined as a percentage of the load since it appears only when the wind production is higher than it can be used, i.e. the load:

Rejected Energy = (Wind P - Used Wind P) / Load

Without low load diesel generator (i.e. a diesel engine able to run at a minimum load), when the instantaneous wind penetration is below 100% there is no rejected energy and the diesel generators have to produce the difference between the load and the wind production. When the wind penetration is 100%, there is rejected energy and the diesel generators stop to run, up to a certain level of rejected energy. In this case, the power balance can be expressed for the two possible cases:

* Diesel P = 0
  Rejected Energy = Wind P – Load
* Diesel P = Wind P – Load (dispatched proportionally to all active generators)
  Rejected Energy = 0

For each value of the time interval the quantities enumerated above were calculated with the model. Then, averages of the results for respective time scales were used to analyse the effect of the time scale on the results.

3.3.2 Diesel Set-Up Operation Modelling

The aim of diesel reaction analysis is to control the effect of the wind fluctuations on the diesel set-up operation. This will be achieved by studying the distribution of the partial loads of the diesel gensets and the number of switching on and off of the diesel gensets in the aim to figure out the effect of wind energy integration on the diesel generators operation and lifetime.

The diesel gensets have to provide the required energy which is not provided by the wind in order to supply the load. They should also respond to most of rapid wind production fluctuations. It will be considered that any voltage variation on the grid will be dispatched proportionally to all active diesel generators.

The set-up controller should be programmed to switch on and off respective diesel generators as a function of their partial load and in the aim to control these partial loads (i.e. mainly avoid overload). Maximal and minimal partial load values should be defined for each diesel, as criteria for switching on and off of this controller. As example, the first generator stop if it runs at less than 70 % and the others provide the required energy. Then, if the active diesel gensets begin to run up to 90 % this one will switch on again, if the second drops below 60 % this one will switch off too, and so on. The importance of adapted limiting value for each diesel genset will be shown later on, with the sensitivity analysis.

The partial load distribution of the respective diesel generators will be followed in order to figure out the effect of wind integration on the diesel operation, but also because their instantaneous partial loads are related to their ability to switching on and off. Indeed, it is important to avoid switching on and off, and particularly the successive switching on and off, in order to minimise possible damage on diesel engines due to wind integration. Successive regime changes will be followed with the model as the fast switching on and off. They correspond to high variations of the wind production in short-time.

The numbers of switching on and off can be minimised with appropriate partial load limiting values and an efficient strategy of control. As remark, the control of the generators, based only on the last partial load value (last 10-minutes/10-seconds/hourly data), is often not enough accurate, due to fast and wide change of these partial loads due to wind fluctuations. The effect of fast switching on and off is too much important to ensure a realistic and efficient system. If the control is based on the maximum of the two previous values, like it was modelled in the computer-based simulation, the effect is significantly reduced. It is also possible to use an average of the previous values, but the results are not so good that they are when the maximum is used.

For the diesel set-up operation modelling, it will be assumed that the four diesel engines are similar. With four **identical diesel generators**, the active diesel generators run at the same power level. When one switches off, the other active gensets take over the load. That could represent high variations of their partial load and affect the diesel, and that is why the maximum value of the two previous is used (as explained in the previous paragraph). The effect of switching on and off, of one of the diesel gensets, on the other active generators will be followed.

It is important to define here that the first diesel to switch off is called the first diesel genset, then the second and third switch off if it is possible, and finally the last to switch off is called the fourth diesel engine. This definition comes directly from the model which takes into consideration four diesel generators for the thesis case study.

It is assumed that the fourth generator switches off too when its partial load is equal to zero. This assumption does not take into account the real effect of low load operation on the normal diesel but enables to observe the effect of the wind fluctuations on the diesel power production.

Fast switching on and off (i.e. successive off/on/off and on/off/on) during 10-seconds are in reality not feasible: a genset needs at least 15 seconds to start-up, as shown in the “Technical Characteristics of WD System Components” part. The results of the diesel reaction analysis at this time scale can be thus compared with others, but it can be also used to study the effect of wind fluctuations on the diesel gensets. This is not observable with the other time scales because one value represents already more than 10 minutes.

The small amount of power, needed at one time in order to avoid a fast switching on, could be the one given at another time in order to avoid fast switching off. This first modelling enables therefore to figure out the possible advantage to include a short term energy storage facility, in order control the system by saving the required energy enough to stop the generator when the partial load of the fourth generator is low.

Finally, the time that a diesel genset is in stand-by was totalised. This time (T Off) is relevant to get the percentage of running time of each diesel generator during the period of study, and thus to figure out how far it is possible to get the diesel generators as much as possible in non-operation.

3.4 Further Modelling for Better Diesel Set-Up Operation

This part presents the possibilities to minimise of the effect of wind fluctuations on the diesel gensets by taking into consideration strategies directly linked to these generators. This seems to be of a prime importance to approach a better WD systems regulation.

In general, generators of same size are installed for purchase and maintenance purposes, such as the availability of replacement parts. However, in WD systems (without battery storage), it is in most of the cases necessary that one diesel generator run all the time in order to respond to rapid variations and drastic decreases of the wind production. Low level of running generators is one of the most appropriate solutions to face this problem. The fourth generator will be forced to run always up to 30 % of its rated power. A smaller size of the diesel gensets or only of the fourth engine could be considered too, in order to study the effect of generators size diversification. In this thesis, only the change of the size of all of the diesel gensets would be considered.

3.4.1 Low Load Diesel

With a Low Load Diesel (LLD) the power balance of the system differs from the previously given balance since the fourth diesel will always run even if at low partial load: the production of the fourth generator will be maintained all the time up to 30% of its nominal capacity (NCd). At high wind penetration, i.e. low diesel production, the respective equations become:

Used Energy = Wind P + Diesel P (i.e. 0.3*NCd at least) – Rejected Energy
Rejected Energy = Wind P + 0.3*NCd – Load

The effect of low load diesel in comparison to the previous case will be to add a constant excess (0.3*NCd) of energy when energy was rejected without low load diesel, and to add a portion of this excess (<0.3*NCd) when the diesel power production was under 30% in the case without LLD, i.e. when the instantaneous wind penetration was high.

Two different strategies will be considered: the diesel genset 4 is always running or is switching off only when it was supposed to stop in the scenario without low load diesel. The effect on the results will be interesting since that could constitute a better approach for further system regulation.

3.4.2 Other Diesel Engine Sizes

Commonly, a diesel set-up in a stand-alone system is composed of 2 or 3 diesel gensets. It could be therefore interesting to consider the case with more or less items, but with smaller or bigger diesel engines.

However, change the size of the diesel is related to the power system design and not directly to WD system regulation. That should be considered in order to see if the effect on the diesel reaction will be better, but that differs from LLD Strategy since the production of the diesel will not be changed:

- LLD strategy change the total diesel production and reduced considerably the effect on diesel generators,
- Another size of diesel engines doesn’t change the production but change the effect on the diesel gensets.

The change the size of the diesel is definitively related to the design of the system, because the size influence the diesel partial load operation and therefore for the same limiting values, the number of switching on and off. That is why this scenario will be considered in the sensitivity analysis.

Thus, the low load diesel strategy will be the only one to be studied since it is directly linked to the diesel operation. It should not be forgotten that the main goal of the thesis is to follow the effect of wind fluctuations on the diesel operation.

3.5 Savings Estimation

The higher the wind penetration is the smaller the diesel production is, and the higher the savings regarding fuel consumption and emissions would be. Therefore, a high enough wind penetration would justify significant savings in comparison to the system operating with the diesel production only, i.e. without wind energy integration.

The characteristics resulting from the design, such as the fuel consumption and the system efficiency, are the figures used for environmental and economic calculations. With a precise diesel engine characteristic curve, the fuel consumption and the emissions could be well defined as a function of the diesel engines partial loads operation, which was described in the previous part. The wind penetration is therefore a relevant parameter to study the effect of the wind fluctuations on the system (diesel reaction: partial load operation, switching on and off) but also to follow the savings that could be awaited with a retrofitted system.

In this report, the savings will be calculated from the difference of produced diesel power between the upgraded system and non-upgraded one. It means that, for a certain number of turbines, the produced diesel power will be compared to the power produced with diesel generators only, i.e. without integrated wind turbines (that corresponds to the case of 0 wind turbines).

The savings of produced power and the effect of these savings on the diesel generators operation will be therefore figured out by the difference between two case (a certain number of turbines and no wind turbine). In the curves, that will be presented in the results part, it will be interpreted as a saving when the curve is above the axis (the engine or set-up runs less than it should run without wind energy) and as an extra production when the curve is below (the engine runs more than it should run without wind).

3.6 Model Presentation

The model was elaborated to use the input data (different time scales of produced wind power from the given and calculated wind turbines data; and a variable or constant load as reference of the demand to be provided) and to process the results announced in the previous paragraphs. The input and output of the model are presented with the figure 3-4 below.

The main goals to reach with the model are:

- To follow the effect of increasing wind penetration (i.e. the number of turbines),
- To study the effect of the time scale on the results,
- To figure out the effect of a variable load combined to the effect of wind fluctuations,
- To include further modelling regarding the diesel generators operation,
- To enable the implementation of the model in order to consider other strategies in a future outlook.

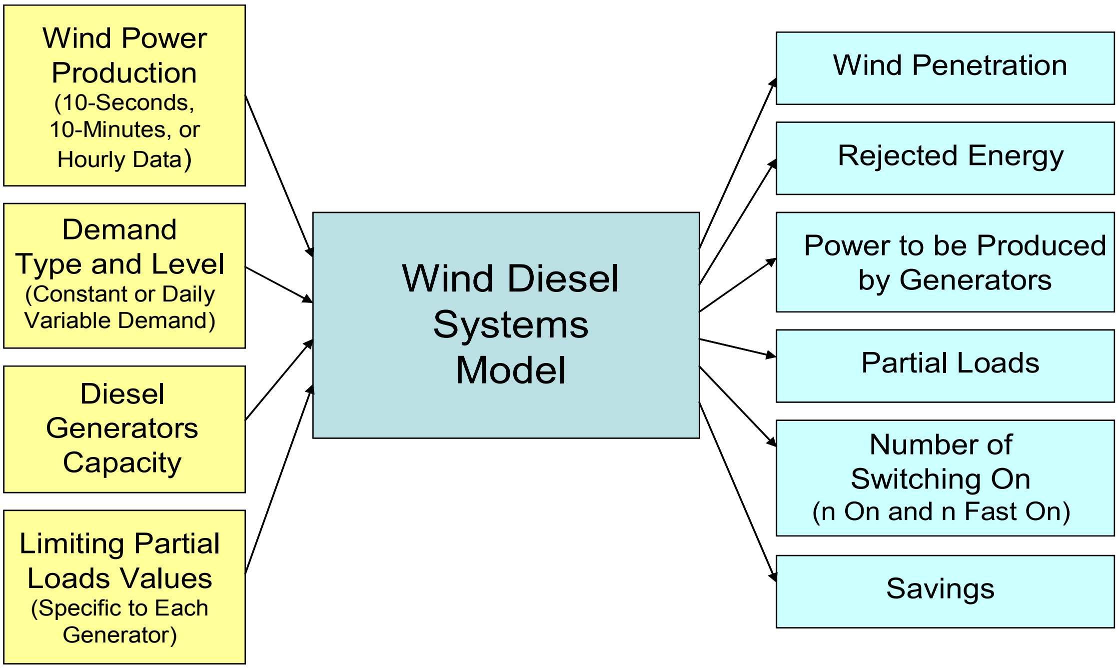


Figure 3-4: Inputs and Outputs of the Model

It is necessary to determine appropriately the inputs in order to operate an efficient study, such as the load level, the number and size of the diesel engines and strategy of the diesel set-up controller (power variation repartition and limiting values of operation). A procedure of usage of the model regarding the inputs insertion, the outputs calculations and the way to reach the goals (presented above and detailed below) is added to the appendices (appendix 5).

3.6.1 Study of the Time Scale Effect

The study of the effect of the time scale on the resulting parameters of WD systems is of prime importance in this thesis. Indeed, some models which can be used to assess the hybrid systems performance and to obtain the inputs required for economic calculations already exist. These are, for instance, Homer, Hybrid2, and Ipsys. However, these models are based on high time scales in order to decrease number of time steps in the simulation (lower requirement of calculation resources). They are therefore not appropriate to follow the effect of wind fluctuations on the stability of WD systems.

This study will be done with two time-scales comparisons: the first comparison will be regarding hourly and 10-minutes data over a long time period (8 days and 5 hours), and the second one will compare hourly, 10-minutes and 10-seconds data over a short time period (8 hours).

For an easier comprehension of the figures in the results part, it is important to precise that the data of the respective time scales will be referred as "Tot" if they correspond to the long time period, or "dt" if they belong to the short time interval (e.g. "Tot 10-Minutes Data", are the 10-minutes data over the long time period).

During the model elaboration, the importance of a precise model calibration in order to obtain valuable comparisons was underlined. This calibration would improve also the accuracy of the model regarding the following points. This necessary calibration of the data and some assumptions are presented at the beginning of the results part.

3.6.2 Processing of the Results for a Variable Number of Turbines

It was presented in the "Wind Data Processing" part that the produced amounts of wind power of 1 to 9 WT were used as the main variable input of the model.

In most of the calculation sheets of the model, the results are processed as a function of one number of turbines. Although the model does not automatic calculations the results for each number of turbines (the number have to be manually changed), it is possible to set the result corresponding to each number of turbine in a common table. From this table it is possible to plot curves for a variable number of turbines. Respective tables related to each time scale enable to compare directly the results of the outputs (for the time scale comparisons presented in the paragraph before).

A first idea was to define the results as a function of the wind penetration and not of the number of turbines. Like that was stated before, both are linked depending on the level of the load, but it was not possible to define all of the results as a function of wind penetration which is an output and not an input. Indeed, even if the demand, which is an input parameter, could be determined (with on-site measurements) in a WD system feasibility study, the wish to choose the right type, number and size of turbines to be installed make not feasible to define the model on the wind penetration directly: this parameter should be kept as an output since it depends on all of the input parameters defined above.

3.6.3 Modelling Without and With LLD

The model includes the possibility to consider the Low Load Diesel case or not (with the choice of one of both strategies exposed previously). If it is chosen that LLD case is considered, the results are recalculated to be compared with the results without LLD, like it is synthesised in the figure below.

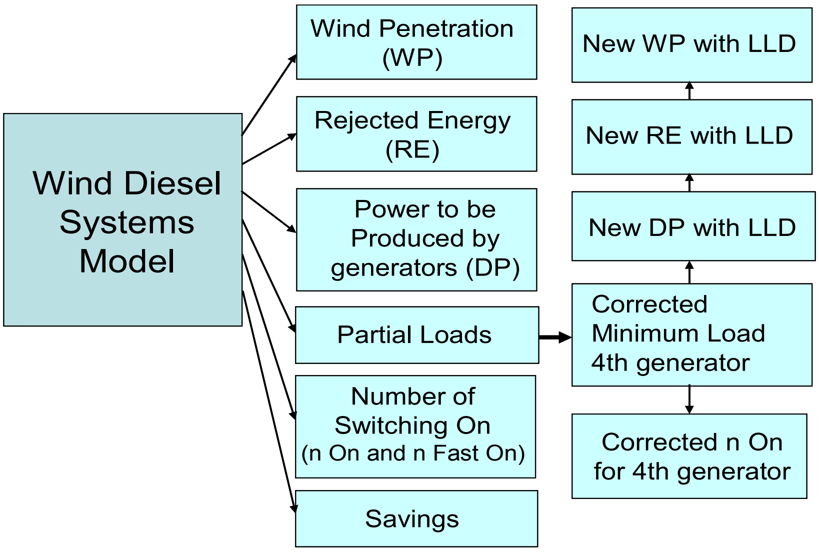


Figure 3-5: Adapted Outputs of the Model for LLD Strategy

The model takes into consideration the partial loads of the fourth diesel engine calculated for the case without LLD and then it adjusts its partial load to 30% is the genset was supposed to run at lower load. Its new production is recalculated and summed for average value result. The rejected energy linked to this extra of production is also calculated, summed and then added to the rejected energy calculating in the case without LLD, which is only due to the excess of produced wind power in comparison to the required load. That gives the new amount of rejected energy. Finally, the new wind penetration is recalculated from this new rejected energy.

3.6.4 Constant or Variable Load Consideration

The level of Load can be varying and then adapted. This was modelled by a factor as input parameter. A constant load of 1,000 kW, or the reference variable load, is multiplied in the model directly by this factor.

The model allows to consider both types of demand: constant or variable before processing the calculations of the results. However, regarding the calculations for the case including LLD, it is not possible to obtain the new wind penetration, amount of rejected energy and diesel energy to be produced for the case of variable load, as easily as it is for constant load. It is due to the fact that these new results were based on the average values, calculated for each time scale and time interval, of the load and the produced wind power. It was relevant for the case of constant load because the average of the load corresponds directly to this constant load, but the results for the variable load case was not relevant since these results should be recalculated for each time values and then used to obtain the new averaging results.

3.7 Sensitivity Analysis

The sensitivity analysis would check the validity of the model by studying the effect of a change of the inputs on the outputs (presented in the previous paragraph “Model Presentation”): all of the results depend on the power system design, which should be achieved before processing the model in order to obtain the results. The sensitivity analysis will therefore carry out the variation of these results with another design. The parameters that belong to the first power system are: the diesel engine size, the level of the demand and the limiting partial load values. Each of these parameters has a specific influence on the results:

- The ***level of the demand*** would change the ratio between the wind power and the demand, i.e. the wind penetration that have the turbines in the system. That should therefore correspond to a better smoothing grouping effect.
- The ***size of the diesel generators***, corresponding to capacity of the gensets, would influence their operation. These generators would run at different partial loads and that could thus influence the diesel reaction.
- The ***limiting partial load values*** would change the diesel reaction by generated more or less switching on and off of the generators.

The sensitivity analysis will thus, in the same time, show if the model is enough efficient in order to optimise the WD system by finding the right conditions of operation, and will also insist on the importance of the design on the set-up controller.

A first idea of sensitivity analysis was to vary the wind data too in order to see the effect on the results. However, that is more related to feasibility study to justify the interest to follow a project or not, as shows a sensitivity achieved for a study [7] about the effect of a change of the annual average wind speed on the cost of energy. The curve 3-6 below, corresponding to this analysis, shows the importance of the wind variation, in comparison to the estimated wind potential. It underlines thus how far a good and appropriate estimation is necessary for wind farm feasibility study.

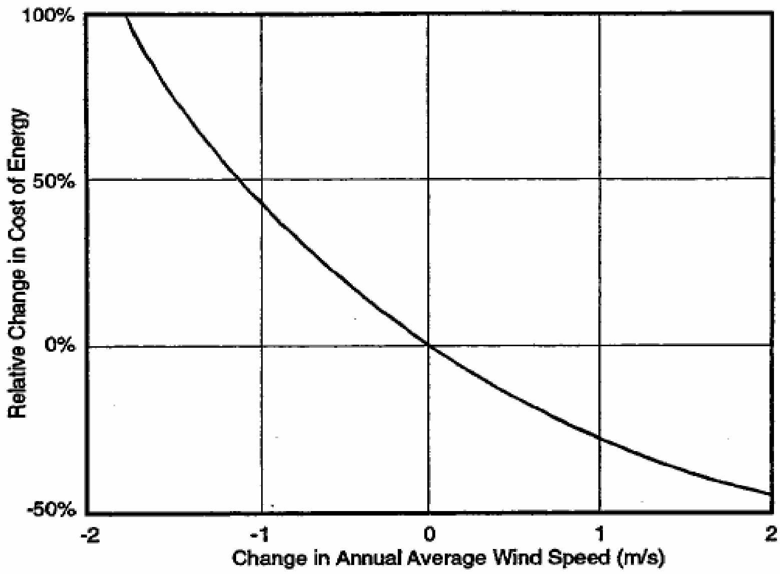


Figure 3-6: Sensitivity Analysis Concerning the Effect of an Annual Average Wind Speed Variation on the Cost of Energy (Source: [7])

The sensitivity analysis will not consider a failure of one of the components. The worst case that was studied in this thesis corresponds to no wind production, what includes the case of a fault in the wind park. It will be assumed that a fault occurs more easily in wind parks than in isolated grids supplied by diesel generators.

4 RESULTS

This part presents all of the results possible to obtain with the model. They concern mainly the wind penetration, the rejected energy, the diesel generators partial loads distribution and their number of switching on in short or longer times.

All of the goals to be reached with the model, presented during the model presentation, will be evoked in the following paragraph and will allow to bring interesting results about WD systems stability in order to discuss the possibility to increase the wind penetration of these systems.

4.1 Input Data, Assumptions and Model Calibration

An appropriated calibration of the model inputs is the first necessary step to use the model. That should be considered to improve the accuracy of the results. This was underlined during the model elaboration, like others important points presented in this part.

- ***Model Assumptions***

The model considers that the diesel engines are able to over take efficiently voltage variations when they run, and also that the diesel set-up controller is programmed according to the model strategy like it was defined in the “Diesel Set-up Operation Modelling” part.

The model is not taking into account the given negative values of produced wind power from the sets of the data acquisition system used as input for the model. These negatives values are probably due to the fact that the turbines generators are asynchronous. These were not considered since the usage of synchronous generators for remote girds supplying was decided like exposed in the “Technical Characteristics of WD systems Components” paragraph.

- ***Model Calibration Requirement***

The input values of the model for the respective time scales for the different time intervals may adequately be calibrated. The first and the last values to use should be carefully determined. That was underlined during the model elaboration with non-sense results: the amount of rejected energy was higher for 10-seconds data than for 10-minutes and hourly data, when it should be the opposite.

This inversion of the results was due to non-calibrated wind production data. This data was first processed, for all of the time scales, from 4:00 to 9:00 (8 days after) for the long time period, and 1:00:00 to 9:00:00 for the short time period. That was not relevant, since a 10-minutes value, corresponding to e.g. 1:00:00, is in fact resulting from the 10-seconds values measured during the 10 minutes before (i.e. from 0:50:00 to 0:59:50), and so on for hourly data calculation.

Table 4-1: Model Calibration Requirements for both Long and Short Time Intervals: Correspondence of one Time Scale to Another for Both Time Invertals

Results Calibration

<table>
<tr><th colspan="2">Long Time Interval</th></tr>
<tr><th>Minutes</th><th>Hours</th></tr>
<tr><td>04:00:00</td><td rowspan="3">05:00:00</td></tr>
<tr><td>...</td></tr>
<tr><td>04:50:00</td></tr>
<tr><td>…</td><td>…</td></tr>
<tr><td>08:00:00</td><td rowspan="3">09:00:00</td></tr>
<tr><td>...</td></tr>
<tr><td>08:50:00</td></tr>
</table>

<table>
<tr><th colspan="3">Short Time Interval</th></tr>
<tr><th>Seconds</th><th>Minutes</th><th>Hours</th></tr>
<tr><td>00:50:00</td><td rowspan="3">01:00:00</td><td rowspan="5">02:00:00</td></tr>
<tr><td>...</td></tr>
<tr><td>00:59:50</td></tr>
<tr><td rowspan="5">…</td><td>...</td></tr>
<tr><td>01:50:00</td></tr>
<tr><td>…</td><td>…</td></tr>
<tr><td>08:00:00</td><td rowspan="5">09:00:00</td></tr>
<tr><td>...</td></tr>
<tr><td>08:40:00</td><td rowspan="3">08:50:00</td></tr>
<tr><td>...</td></tr>
<tr><td>08:49:50</td></tr>
</table>

During the model elaboration another important point was underlined: there is a small variation between the results obtained with given 10-minutes data and with calculated 10-minutes data from the 10-seconds data. This is probably due to the fact that given 10-minutes data was calculated from stored and rounded measured 10-seconds data. The 10-minutes data should therefore better be calculated from 10-seconds data in order to study further the influence of the time scale. For the thesis, the results were calculated from given data and were corrected. The factor used for this correction was based on the difference between produced wind power for 10-minutes and 10-seconds, since these values should be equal in theory.

- ***Number of Values Available for Calculations***

The problem mentioned above occurred during the elaboration of the short time period comparison only. This shows that the short time interval is much reduced, particularly for hourly based data and this underlines the importance of the width of the time interval in order to have reliable and realistic results for each number of turbines. Indeed, the short time interval corresponds to 2879 values of the 10-seconds data, 49 values of the 10-minutes data, and only 8 values of the hourly data. The influence of the quantity of values available for calculations is exposed in the appendix 6 with the curves for the respective time scales for 4 and 8 turbines.

High quantity of wind production values for the respective time scales are thus required, since the model is sensitive to the width of the time interval, which is obviously much reduced for higher time scales of the processed data.

It was a first idea of possible goal for the thesis to determine some correction factors. These should be useful for better WD system reaction prediction, by approaching further more the relation between the predicted reaction (based on hourly or 10-minutes data) and the expected real reaction (related to secondly wind fluctuations). However, the limited quantity of values for the short time interval gives a significant variation of the 10-minutes and hourly based results between long and short time periods, and make difficult to obtain of correction factors.

4.2 Power System Design

This part is related to the first sizing of the equipment. In the case of this study, the most important to design previously is the required diesel generators capacity. Regarding diesel generators installed capacity, it can be designed with the model. The design includes the diesel gensets capacity but also the partial load limiting values, used as criteria for switching on and off the respective generators as explained in the methodology part. However, this first design would have to be adjusted and corrected for the number of turbines, chosen as optimal for a special case-study.

Before defining this design, the load should be adjusted and fixed in the model in order to have large range of wind penetration. It should be remembered that the wind penetration depends on the type and level of the demand and the type, size and number of turbines (with predefined type and size in the case of interest for the thesis). For a high load, e.g. a constant demand of 8,000 kW in this case-study (factor of 8, see "Model Presentation – Constant or Variable Load Consideration" paragraph), the resulting wind penetration values vary under 50 %. For a low load level, e.g. constant at 2,000 kW (factor of 2), the wind penetration varies widely under 80 %. Since it is not important to have high resolution of the results (i.e. many values) at low wind penetration, because it is more important to have a wide range of wind penetration values, it is more interesting to choose a low load level. A factor of 2 was taken as fixed for the processing of all of the following results.

In order to approach an optimal design, the model enables to quantify two major problems which makes the design non feasible. These problems are related to overload of one or more diesel gensets. It is considered that the diesel generators are overloaded when they should run at partial load higher than 100 % of their rated power. Moreover, if a genset is overloaded it will switch off in order to protect itself, due to the fact that it can not provide the required power. These problems are:

- The first problem corresponds to a lack of power into the system due to an under-dimensioning of the installed gensets rated power. The overall capacity of the gensets is therefore not enough to provide the required energy and the total installed capacity should be increased. This problem is not directly linked to WD systems design but more to supply security matters.
- The seconds is further specific to WD systems design: only the fourth diesel engine can not supply the power that it is supposed to provide. It is due to a non-optimised switching off of the third genset: the third genset switches off, but should not, since a small increase of the wind speed just after its switching off is enough to generate the overload of the fourth generator. This problem, which should be avoided as much as possible, can be minimised with an appropriate partial load limiting factor used as criteria for the switching off of the third engine.

The numbers of times that each problem occurs in the system were quantified with the model. These problems should be avoided as much as possible since that will result in a fault on the grid due to the disconnection of the generators. If these disconnections would not damage the system and the electrical devices, an acceptable number of times that the system is supposed to disconnect for a certain period could be defined according to the tolerance of the local users and the availability of maintenance possibilities, which would be the first limit to this disconnection acceptance.

The other aim of the power system design is to figure out feasible and effective limits for diesel generators switch off in order to avoid the second problem mentioned above, but also to reduce the number of switching on and off of the generators in the same time. A first power system was done during the model elaboration, it corresponds to the following used parameters. The relevance of these figures will be discussed in the sensitivity part, since it fixes the context of the study and influences the results directly.

Table 4-2: Chosen Inputs Regarding Diesel Engines Operation, at a Preliminary Stage of the Power System Modelling

Pnom Diesel (kW)	1200

Diesel Engines Off & On Limits:

Off 1	80%
Off 2	50%
Off 3	20%
On 1	90%
On 2	80%
On 3	60%

4.3 First Model Interpretation

A first interpretation would be to see the effect of wind power on the power balance of the whole system. The figure 4-1 is a simple representation of the power flows for a fixed number of turbines. This curve was plotted for 10-minutes data over the long time period for a wind penetration of 58.6 % (corresponding to a number of turbines of 6, in the figures 4-2 and 4-3 below). In this case the average rejected power is 31.13 % of the load, while the maximum of the rejected power is around 70 %. This is particularly important to be considered to dimension the dump load device.

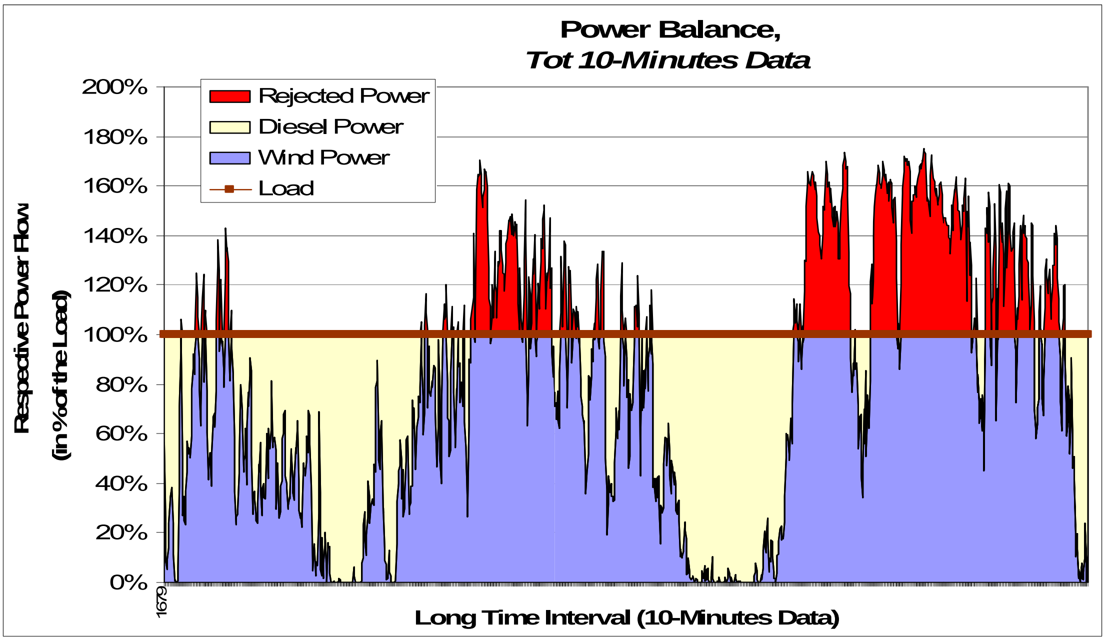


Figure 4-1: Power Balance in Percentage of the Load for 6 integrated WT, 10-Minutes Data over the Long Time Period

Then the power balance, i.e. the respective power percentages (% of the load), versus the number of turbines can be plotted. This curve shows the important increase of rejected power for high number of turbines while the wind penetration is not any more significantly influenced by the number of turbines.

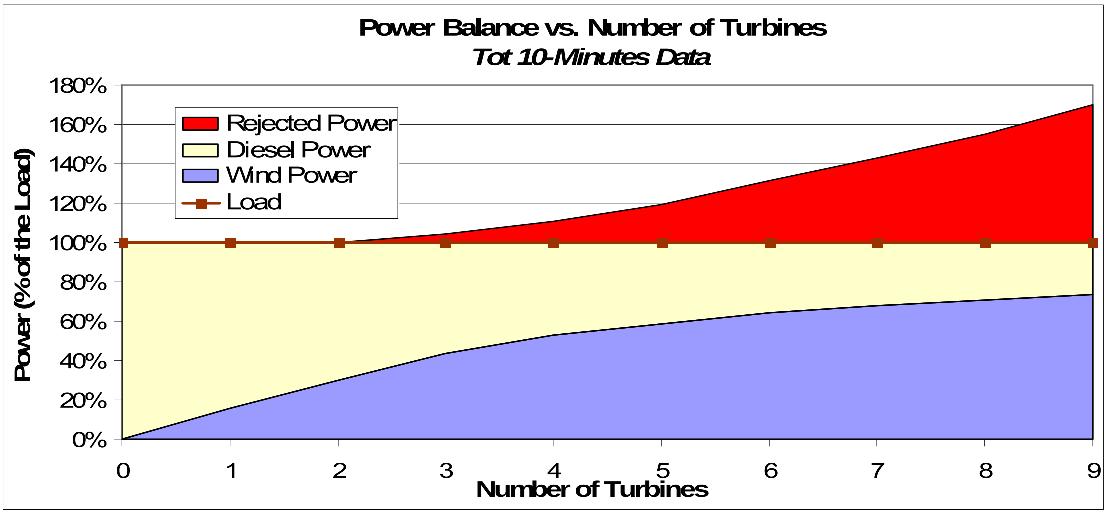


Figure 4-2: Power Flows in Percentage of the Load vs. Number of Turbines, 10-Minutes Data over the Long Time Period

A variant of the previous curve presented below underlines that the diesel set-up has to produce a constant amount of power when the average wind production is higher than the load. This occurs for a number of turbines superior to 6. Install more than 6 WT will increase the wind penetration of the system, but will not enable to save diesel power.

Therefore, in this case, there is no interest to increase the wind penetration by installing more than 6 WT without storage strategy, but there is the possible interest to store wind power for WD system with more than 6 WT: the rejected power and diesel power production could be partially, maybe mainly, avoided.

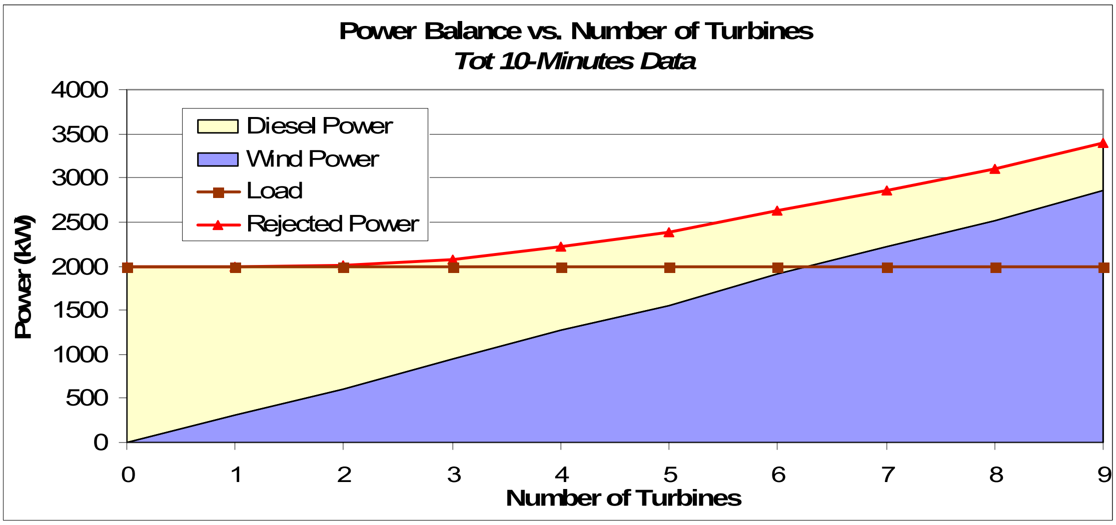


Figure 4-3: Power Flows in the System vs. Number of Turbines, 10-Minutes Data over the Long Time Period

4.4 Wind Power Flows

This part presents the results of the modelling obtained for the wind penetration and the rejected energy as a function of the number of turbines.

4.4.1 Average Wind Penetration

The relation between number of turbines and wind penetration is linear for lower wind penetration values. That is due to the fact that there is no rejected energy at low wind penetration. In this range, the wind penetration is therefore directly proportional to the number of turbines, i.e. the ratio between the load and the wind power is constant when there is no rejected energy produced in the WD system.

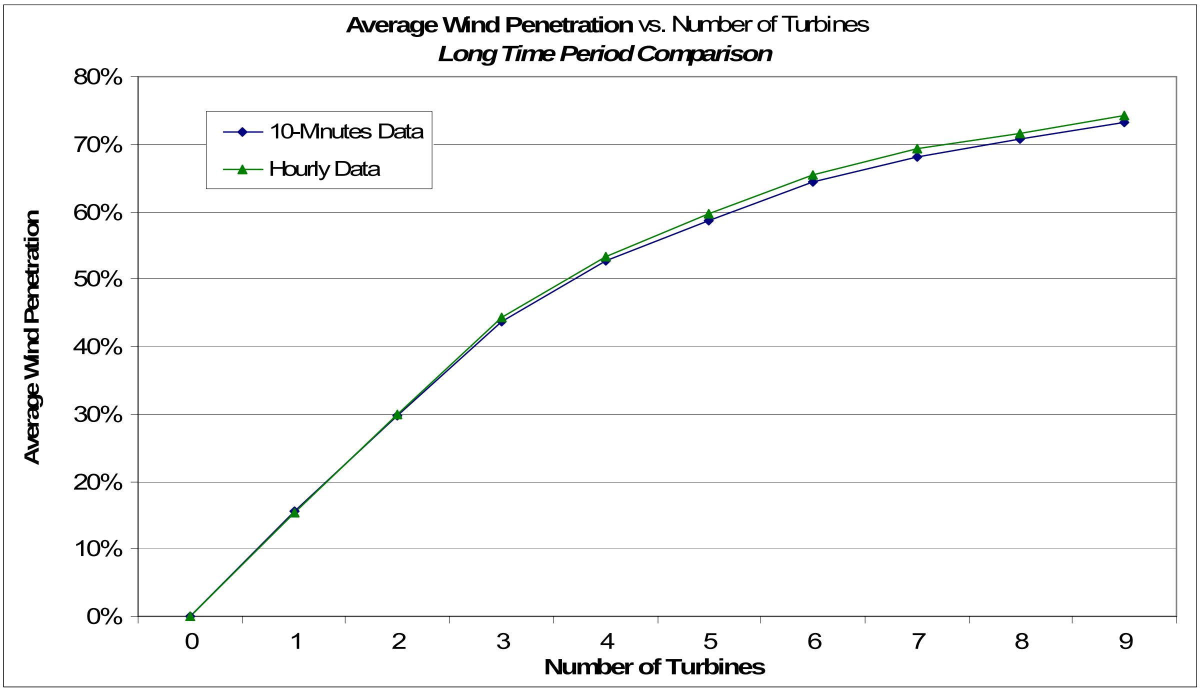


Figure 4-4: Average Wind Penetration vs. Number of Turbines, Time Scales Comparison over the Long Time Period

4.4.2 Rejected Energy

Before all, it should be remembered that the amount of rejected energy presented in this part does not take into account the eventual rejected energy appearing with a low load diesel or even with a dump load strategy like evoked in ”Other Elements for WD Systems Regulation” Part.

The amount of rejected energy rises not proportionally to an increase of wind penetration. At higher wind penetration values, the rejected energy increases mush faster than the wind penetration. The installation of an additional turbine in the system would have a significant impact on the total amount of rejected energy while the impact on the resulting wind penetration is limited: as shown by the figures 4-4 and 4-5, the variation of the rejected energy between 8 and 9 WT is +15 %, when the corresponding variation of the wind penetration is only +3 % approximately.

There is therefore no sense to increase a little the wind penetration if it results important quantity of rejected energy, and particularly if the excess of energy is dumped and not use as energy source for other applications.

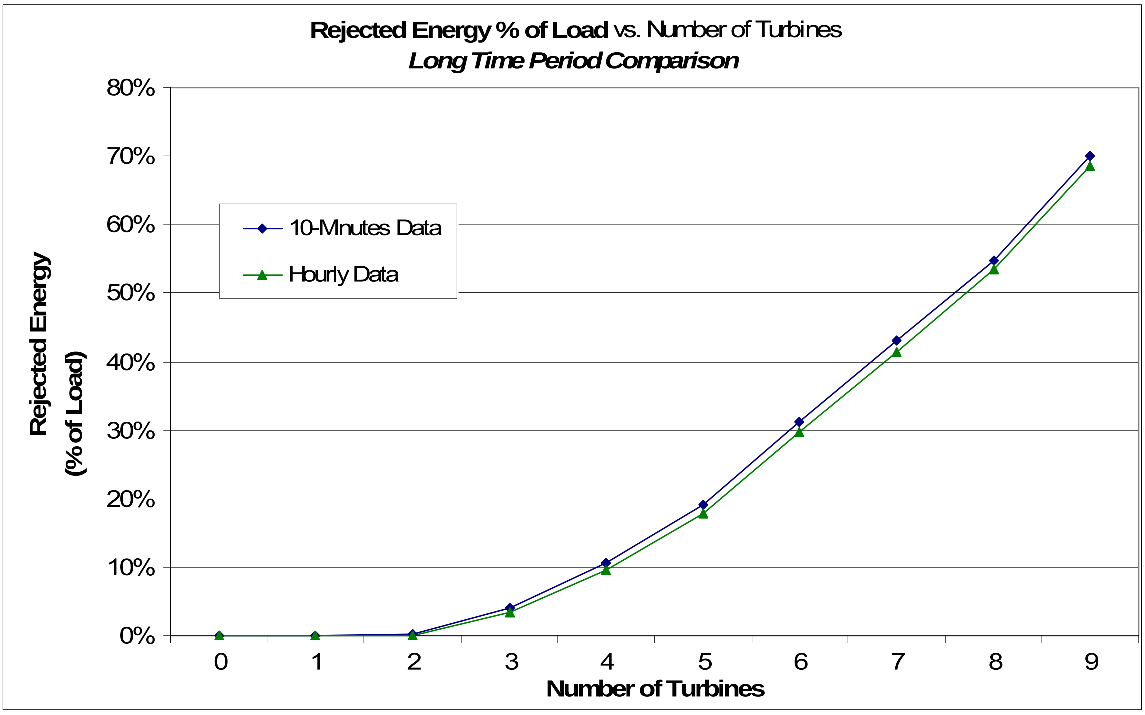


Figure 4-5: Rejected Energy vs. Number of Turbines, Time Scales Comparison over the Long Time Period

4.4.3 Time Scale effect

The figures below present the same curves than the two previous, but these result from the comparison over the short time period. Time scale comparisons about wind penetration and rejected energy bring interesting conclusions valid and applicable to all of the results obtained in the aim to study the effect of the time scale, e.g. the results about the diesel engines operation or the savings.

In consideration to the long time comparison, the amount of rejected energy should be close for hourly and 10-minutes results, and they should particularly begin to appear in the system for the same number of turbines. Then, the wind penetration is generally lower during the short term interval, since the rejected energy is produced for more than 4 turbines, while it is for 3 WT with the long time period comparison. The rejected energy calculated over the short time period is also significantly lower than it is for the longer time period.

The results corresponding to the short time interval are therefore less precise than the results for long time period, and this confirm the influence of limited quantity of values used for calculation. These results show also that the input data related to this time interval, are not enough representative of the real behaviour of the wind during a longer period. The long time period is thus surely the most representative of the system behaviour.

WD systems behaviour can be therefore well expected, but that has to be achieved over longer time intervals of input data. However the consideration of the wind fluctuations, by using small time scale, is definitively important to predict it as much as possible, even if this means that more 10-seconds data should be available for calculations.

Independently to the previous remarks it can be concluded that the results for the 10-seconds data are close to the ones for 10-minutes data, there is no significant difference between both time scales results.

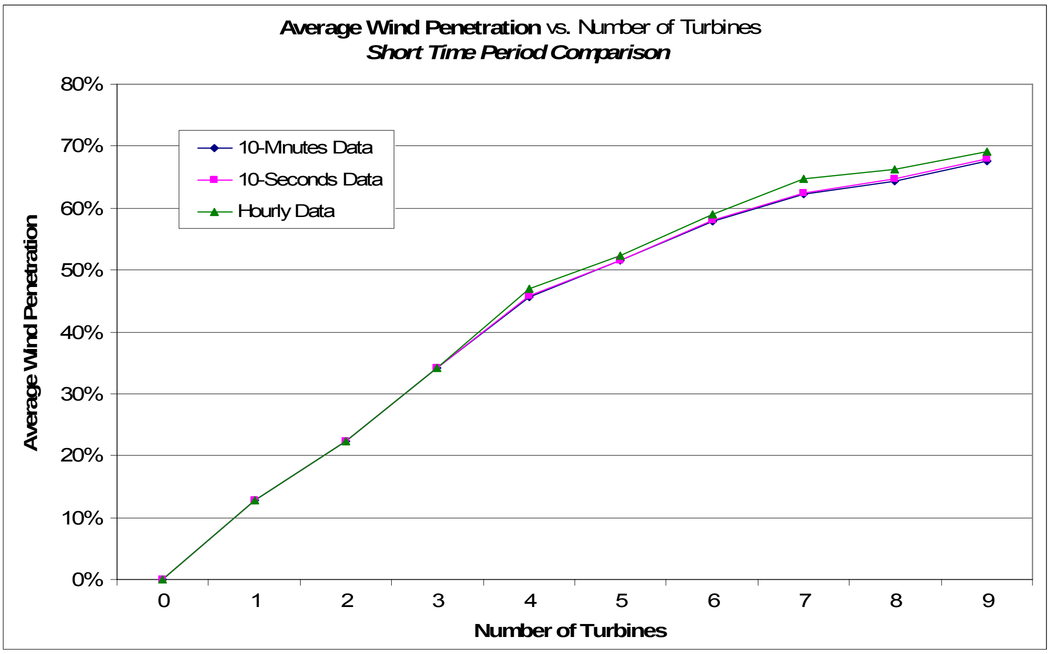


Figure 4-6: Average Wind Penetration vs. Number of Turbines, Time Scales Comparison over the Short Time Period

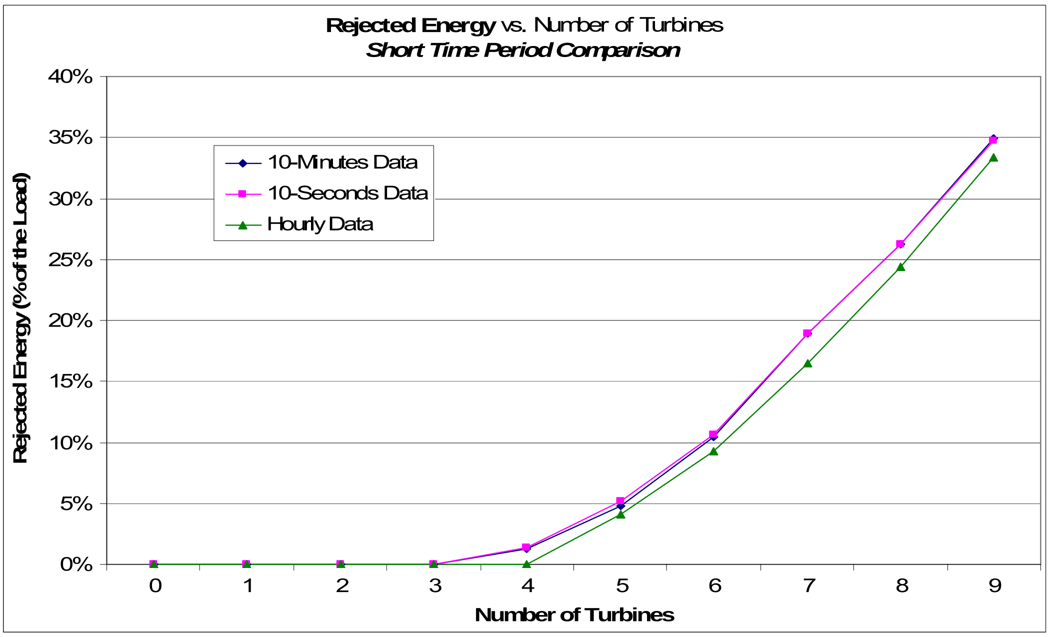


Figure 4-7: Rejected Energy vs. Number of Turbines, Time Scales Comparison over the Short Time Period

4.5 Diesel Generators Reaction

The integration of wind power has obviously an effect on the diesel reaction, which can first be seen as a decrease of the running time of respective diesel generators.

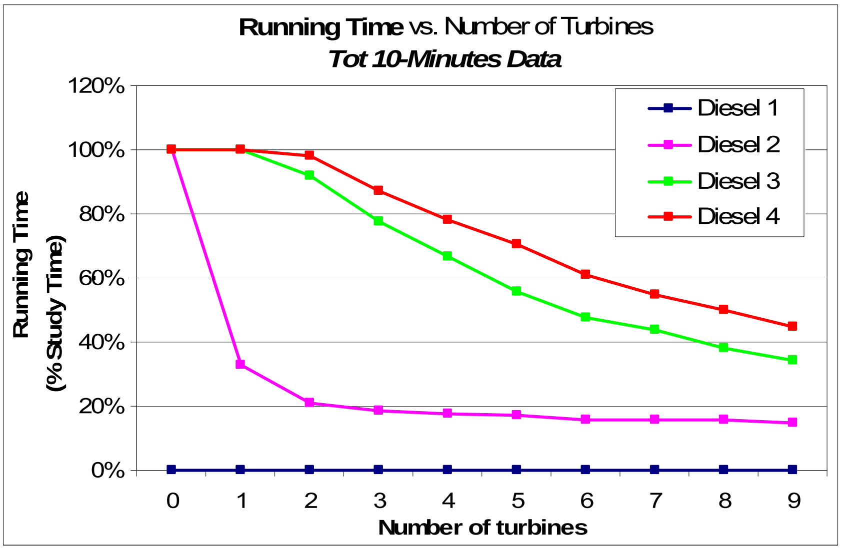


Figure 4-8: Running Time of the Respective Gesets vs. the Number of Turbines, 10-Minutes Data over the Long Time Period

Without wind turbine, three diesel gensets run to provide the demand. All of them are working at constant load between 60 and 70 %. With the integration of wind power, the effect of wind fluctuations on the diesel operation is to influence the engines by varying their partial loads and making them switching on and off, even more at high wind penetration.

In order to optimise the diesel set-up operation, the variation of the engines partial loads and the number of switch off and on should be minimized and any problem resulting in a disconnection of the grid due to high voltage variations should be avoided as much as possible.

4.5.1 Partial Load Operation

It is possible to figure out with the model at which regime run the diesel generators as a percentage of the running time. The figure 4-9 below shows the respective diesel engines partial loads with 6 WT for the long time interval. It shows the importance of the effect of the wind fluctuations on the diesel operation, what could stress the diesel generators.

It is important to remember that the diesel engines switch off if their partial loads are below their respective limiting off values (the diesel 4 has no limiting off value if the LLD modelling is not considered), and switch on if their partial loads are above their limiting on values. It happens that their partial load decreases so fast that the change of state (on or off) is done after a lap of time, which corresponds to the time required to get a new time value taken into consideration by the diesel set-up controller. This lap of time is particularly important to be considered with 10-minutes and hourly data.

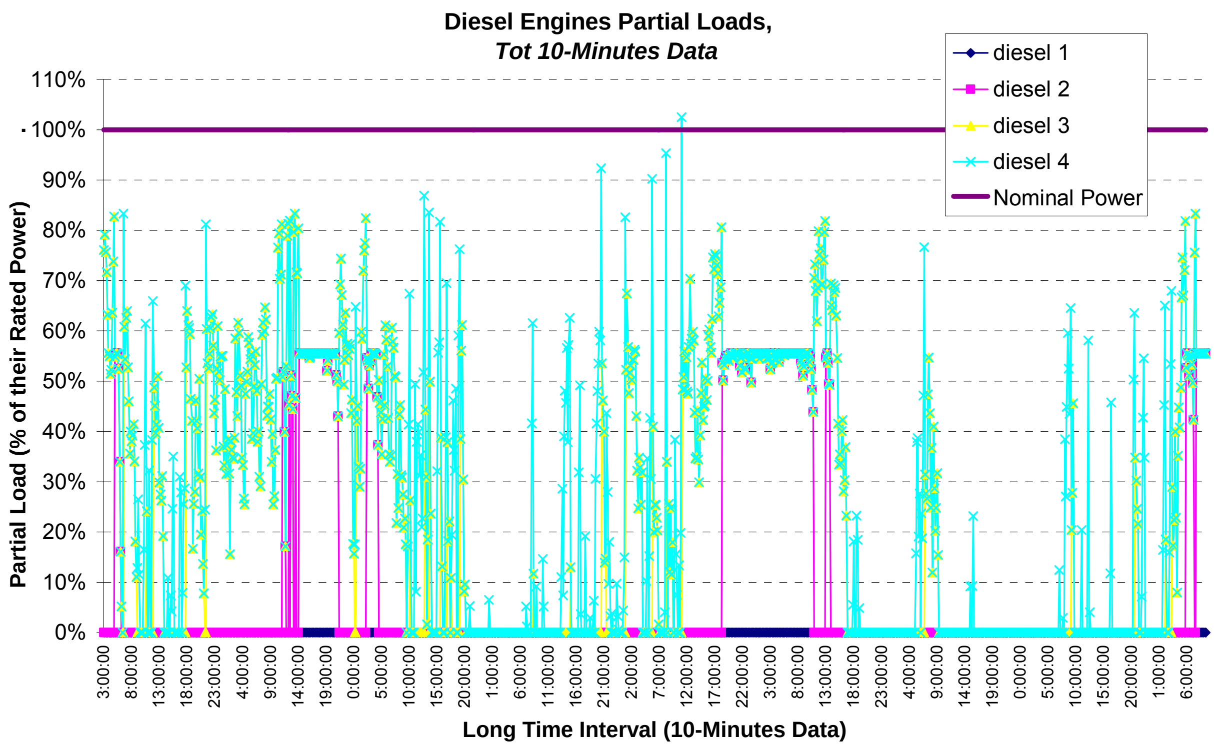


Figure 4-9: Diesel Engines Partial Loads with 6 integrated WT, 10-Minutes Data over the Long Time Period

The plot of the distribution of partial loads enables to follow the effect of the wind fluctuations with the proportion of time that the gensets are running in a certain range of partial load. This distribution gives an idea about the generators load variations between two ranges of partial load, what is linked to the wind fluctuations. It is useful to figure out the possible stress that could affect the gensets, according to the fact that diesel engines should operate in an optimal range of load.

The figure 4-10 is the representation of the partial load distributions of the respective engines. It underlines the influence of the chosen limiting partial loads values on these distributions. That can be clearly observed with the second diesel partial load distribution: it is running mainly between 50 and 80 %, like that was fixed by the limiting values, while the distributions of the engines 3 and 4 are spread. The distribution of the partial loads is thus directly linked to the early chosen limiting values, since these define the limit of operation of each diesel. The importance that different and adapted limiting values are chosen for each diesel generators will be further demonstrated with the study achieved for the sensitivity analysis.

Concerning the third engine, the limiting values could be adapted in consideration that its limiting off value should be enough low in order to avoid too fast switching off of this one, what would provoke an overload of the genset 4 if wind regime grows up just after (refer to the “Power System Design” part). However, this limiting off value should be carefully adapted in order to avoid that the third engine runs at partial loads below 40 % (at least 30 %). These requirements regarding limiting on and off values have the effect to spread the distribution of the diesel engine 3, and the effect of these values on its reaction should be therefore carefully considered.

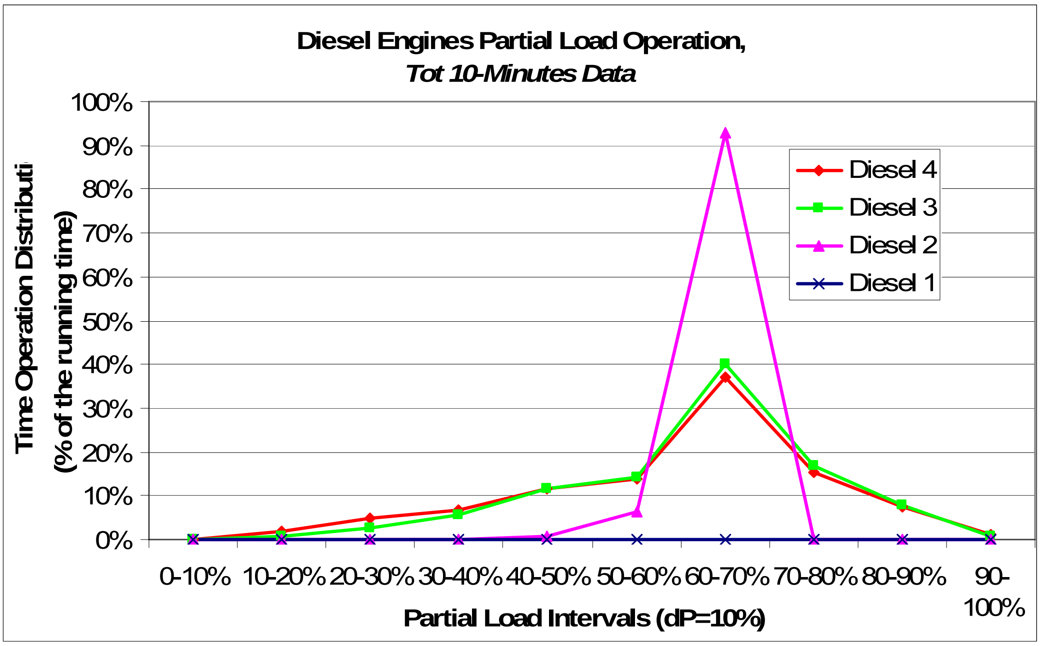
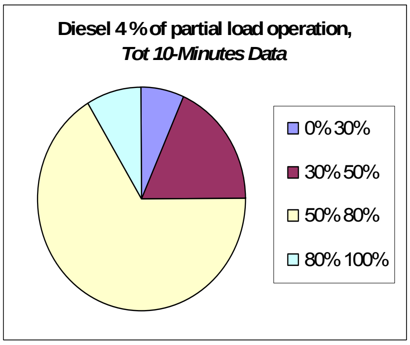
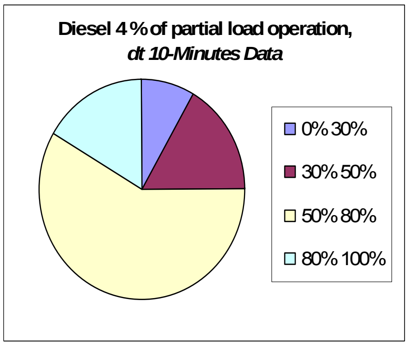


Figure 4-10: Diesel Engines Partial Load Distributions with 3 WT, 10-Minutes Data over the Long Time Period

The figure 4-10 shows in the same time an expected interest to have one or even two low load diesel engines. The case with one low load diesel will be considered in the LLD Part, but the possible benefits to have two LLD generators in order to decrease more significantly the effect of the wind fluctuations should be also considered, even if that would be linked to higher investment costs.

It is also possible to represents the partial loads distribution in a pie chart The two figures below enable a comparison of the diesel engines operation results for the different time scales. In these, the results for 10-seconds data could be chosen as the better approach of the real system behaviour. The first chart shows that the engines are running further at partial loads between 30 and 50 % that it could be expected with 10-minutes data, and the second shows clearly that higher and lower partial loads are not observed so often with 10-seconds data. It can be concluded that in reality the diesel engine partial loads vary widely between upper and lower partial loads but are mainly in acceptable range of partial loads.





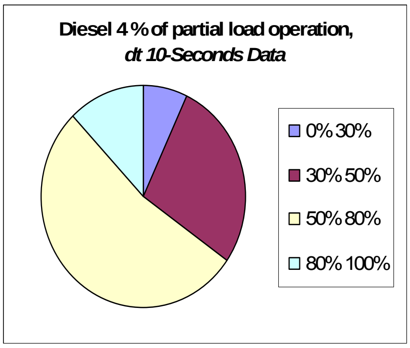


Figure 4-11: Fourth Diesel Engine Partial Load Distributions with 3 WT, Time Scales Comparison over the Short and Long Time Periods

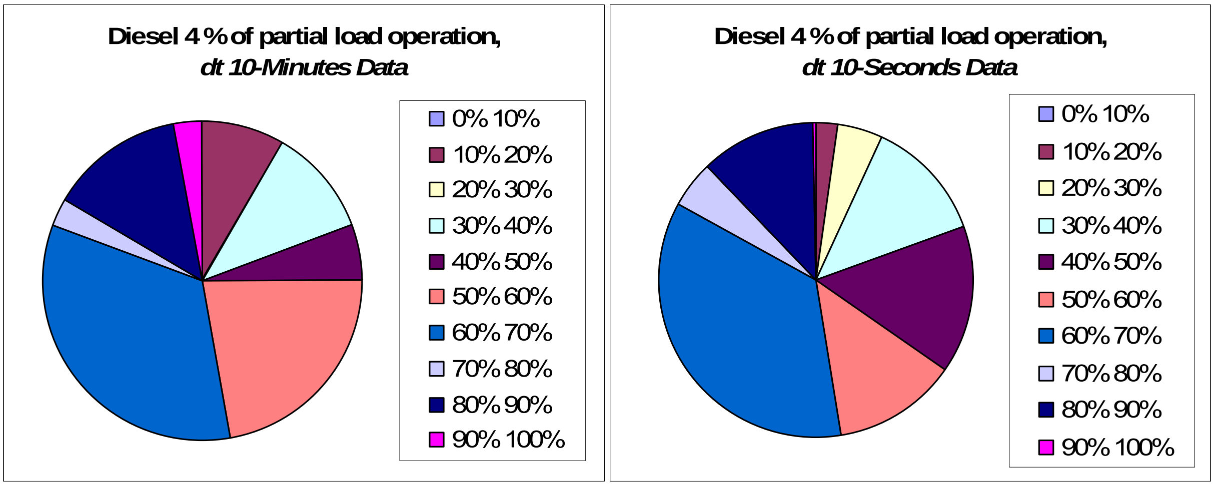


Figure 4-12: Fourth Diesel Engine Detailed Partial Load Distribution with 3 WT, Time Scales Comparison over the Short Time Period

4.5.2 Switching On and Off

The second approach is to plot the number of time that each diesel generators is switching on and off, due to the wind fluctuations. It is possible to make a difference between the number of times that the diesel is switching on or off, for a long time or for a short time. A switching on or off occurring fast means that in the time of two values only the concerned diesel genset is switching on or off (i.e. for less than 10-minutes, 10-seconds or one hour). These numbers (respectively called n On/Off and n Fast On/Off) will be the interest of this part.

Table 4-3: Sample of the Model Regarding Diesel Operation Calculations

diesel 2	%prod2	TOff	nOff	nFastOff	nOn	nFastOn
0,00	0	1	0	0	0	0
2193,97	0,5224	0	0	0	1	1
0,00	0	1	1	0	0	0
0,00	0	1	0	0	0	0
2278,62	0,5425	0	0	0	1	1
0,00	0	1	1	1	0	0
2236,59	0,5325	0	0	0	1	1
0,00	0	1	1	0	0	0
0,00	0	1	0	0	0	0

As shown in the table 4-3, these figures were previously calculated, and it was underlined that n On reflects well the number of time that a diesel is switching on and therefore off later on. The numbers of switching on and off can therefore be considered as equal, what is not the case for numbers of fast switching on and off. The example below shows that the second diesel switches on and off three times. Only one fast switching off is counted, while three fast switching on are counted. n Fast On is therefore more appropriate and reliable to follow the fast switching on and off. That is directly due to the fact that T off (number of times that the genset is off during the study time) was used as reference for their calculation.

Only the number of n On and n On Fast were thus taken into account, as criteria to study the influence of the whole system on the diesel generators lifetime. However, for the fourth diesel, the number of fast switching off is important since it represents the number of times that the diesel is switched off but should not. Fast switching on of the second diesel was considered in the detailed curve too, but only in order to check that it is always lower than fast switching off.

The number of time that a diesel switches on could be analysed for the respective diesel gensets or for the whole diesel set-up, what enables to compare the results for the respective time scales. A good compromise between n On and n Fast On has to be found: both should be reduced, with n Fast On as much low as possible.

The fact that fast changes appeared is linked to the non-optimisation of the diesel reaction, because it means that the diesel is switching off and on for only one value took into account. This underlines the fact that 10-minutes value are not enough sensitive to be relevant as basis for diesel controllers programming. 10-seconds values could provide more sensitive values to wind fluctuations and provide better basis for diesel reaction optimisation.

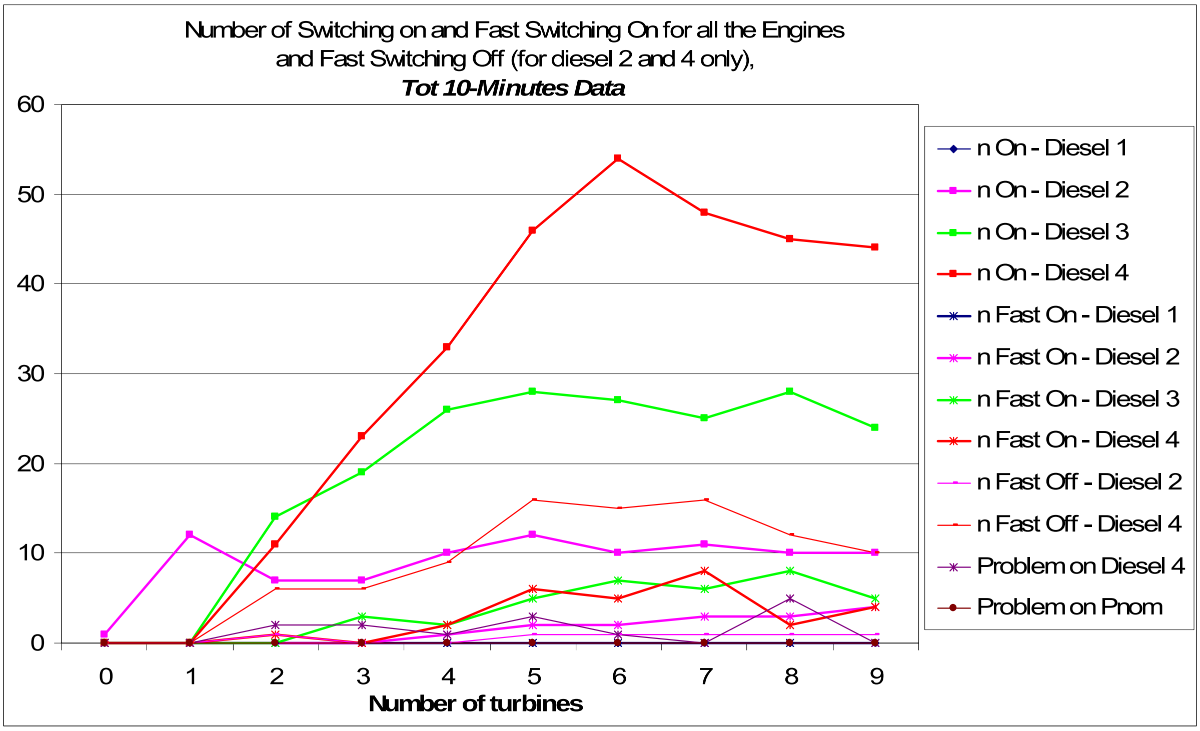


Figure 4-13: Number of Switching On and Fast Switching On for all of the Engines and Fast Switching Off for the gensets 2 and 4, 10-Minutes Data over the Long Time Period

The number of times that the problems occur in the diesel set-up, evoked in the “Power System design” part, are represented in the detailed graph concerning the respective diesel gensets. It can be remarked that these numbers are low even if the problem, which arises due to fast switching off is minimised, even if it could be important for some number of turbines (e.g. 8 WT).

The detailed curve above shows, that the total number of times that the gensets switch on (see curve below) is mainly due to the diesel generators 3 and 4. With an observation of the successive calculations achieved by excel to obtain these results, it was remarked that the wind fluctuations are mostly overtaken by the genset 3, because it switches on and off most of the time fast or for short time intervals.

Generally it can be stated that, at low wind penetration values the second and third diesel generators are more influenced (in consideration that the diesel 1 is almost in stand-by), and at high wind penetration values the fourth is further influenced. As remark, the raise of the number of switching on for the second diesel, corresponding to 1 WT, is due to the fact that it is running at partial loads near to the chosen limiting value. For a small wind penetration increase (i.e. 2 or 3 WT) the diesel is switched off more often, and thus reacts less. For a higher wind penetration increase (more than 4 WT) the reaction of this genset becomes again to be higher. That is probably due to the increase of the wind fluctuations, (which increases obviously with the wind penetration and thus the number of turbines), like it is the case for the generators 3 and 4.

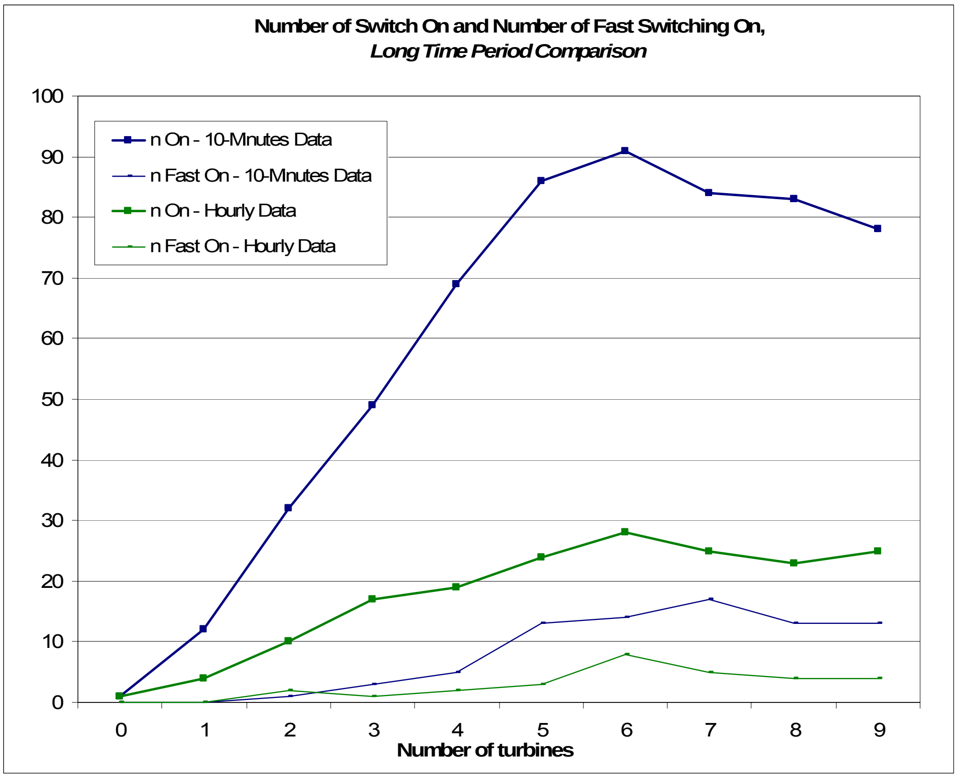


Figure 4-14: Number of Switching On and Fast Switching On vs. Number of Turbines, Times Scales Comparison over the Long Time Period

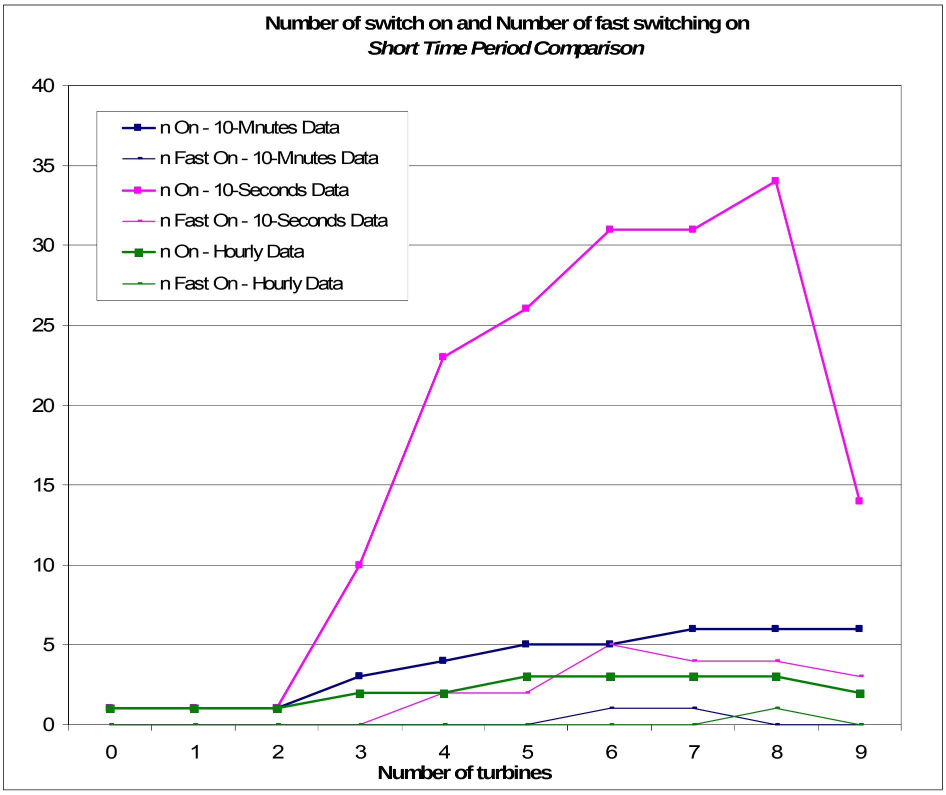


Figure 4-15: Number of Switching On and Fast Switching On vs. Number of Turbines, Times Scales Comparison over the Short Time Period

The main previous curve shows therefore that the diesel gensets (mainly the fourth in this case) is switching on and off significantly more often with 10-seconds data than it can be expected with 10-minutes or hourly data. Moreover, it does not switch on fast so often (i.e. only for 10 seconds, what is taken into account by the model and plotted in the curve), but it switches on for short time period (20 or 30 seconds).

It should thus be remembered that the number of the switching on and off is significantly influenced by the wind fluctuations, but also by the level of wind penetration, i.e. the level of power to be produced by the diesel set-up, and then by the limiting values regulating this diesel set-up.

4.6 Expected Savings

Follow the savings is interesting because there are related to the savings of produced power by integrating wind power in isolated grids. However, it should not be forgotten that the diesel generators operation is much more preoccupant, since if the WD system doesn't work, there would be no savings. Therefore, the saving concerning diesel production and the effect of saving on the diesel operation will be analysed in this part.

4.6.1 Diesel Production

The savings on the diesel production was figured out with the total energy produced by the set-up or the respective engines. These savings are shown in the figure 4-16. In this part the savings are calculated on the total energy to be produced during the considered time interval (the long time period in the presented curves). These savings are directly linked to the running times of each engine.

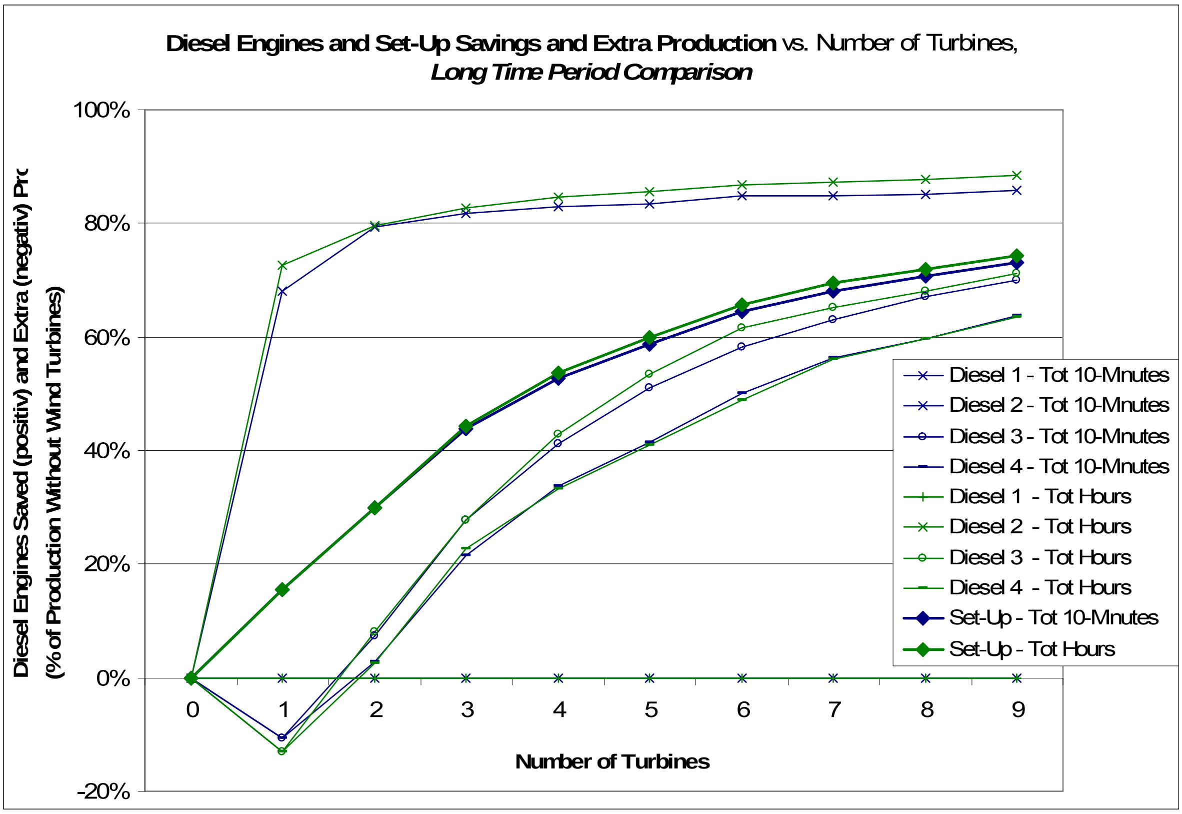


Figure 4-16: Diesel Engines and Set-Up Saved and Extra Productions vs. Number of Turbines, Times Scales Comparison over the Long Time Period

As it can be seen, the savings on the diesel genset 2 are very fast significant. Even for 1 WT, the diesel engine 2 runs less while the diesel gensets 3 and 4 produce more. This shows that these generators take over the load managed previously by the genset 2 by producing a bit more, but this is only for 1 integrated WT. By the way, the total saved energy is fast significant. More than 50 % of the set-up production without wind energy integration is saved with 4 WT.

For the short time interval the results are similar (given in the appendix 8), but the instability of the results for hourly data shows clearly the influence of the number of values used for calculation. The results for 10-minutes and 10-seconds are similar, but there are much more important than they are for hourly data.

4.6.2 Diesel Operation

The savings on the diesel operation concern the effect of wind energy integration on the operating partial load regimes. In this part, the savings or the extra productions are thus followed as an influence of wind power integration and fluctuations in the system on the distributions of the diesel engines partial loads. As stated in the methodology part, this influence is interpreted as a saving when the curve is above the axis, and as an extra production when the curve is below.

The figures presented below show the effect of the integration of 3 WT on the distribution of the partial loads of the diesel generators and the overall diesel set-up. It was plotted for each time scale and time interval. It is presented here for 10-minutes data over the long time period. Then, the figures 4-18 show the results for the respective time scales over the long time period too.

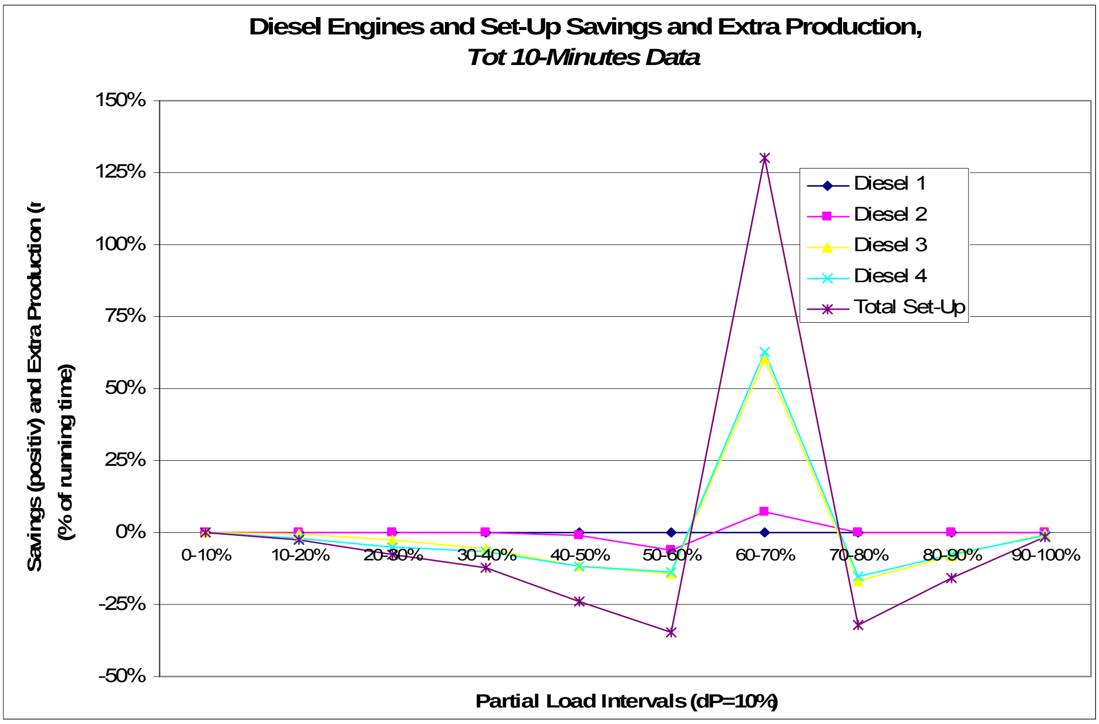


Figure 4-17: Saved and Extra Productions Regarding Diesel Engines Partial Loads Operation with 3 WT, 10-Minutes Data over the Long Time Period

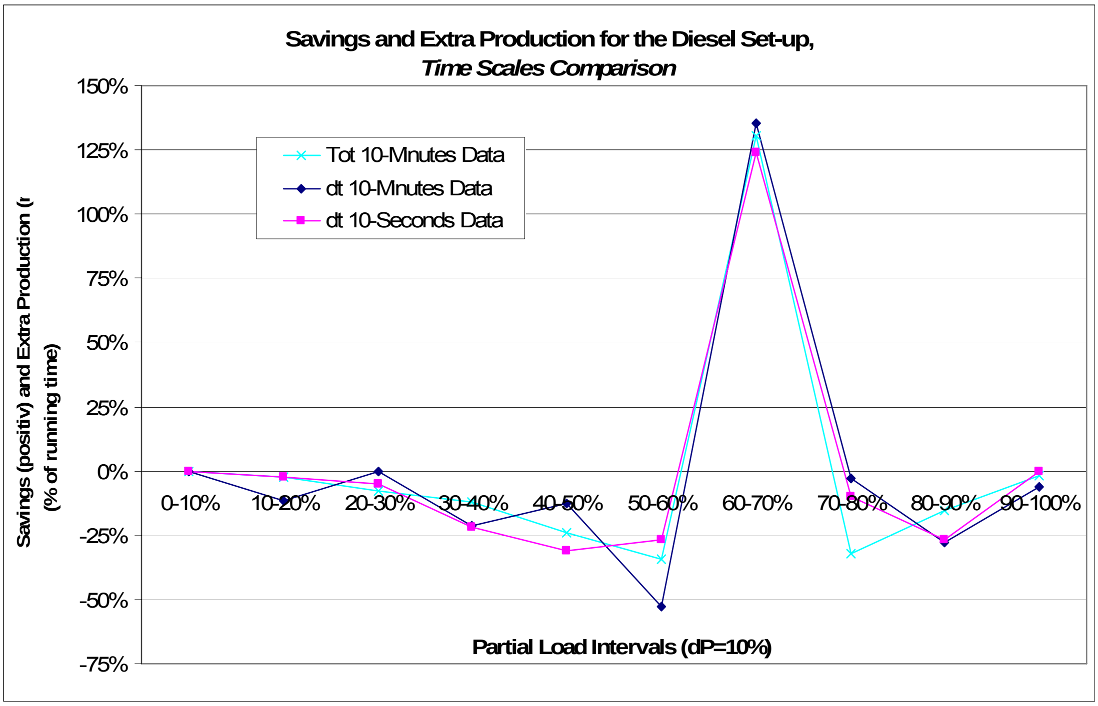


Figure 4-18: Saved and Extra Productions Regarding Diesel Engines Partial Loads Operation with 3 WT, Time Scales Comparison over the Short and Long Time Periods

This curve shows the influence of the time scales on the diesel operation. The 10-seconds results show that the generators run in reality in a widely range of partial loads (more important for this time scale between 20 and 50 % and above 80 %), less at very low partial loads (0 to 20 %) and more at middle loads (between 50 and 70 %) than it is for 10-minutes and hourly data.

Finally the next figure underlines the relation between the number of turbines and the effect on the diesel set-up operation: for 1 turbines, the active diesel engines are running more at high partial loads (i.e. they are often overloaded) and for more wind turbines the diesel generators are running even more at low partial loads.

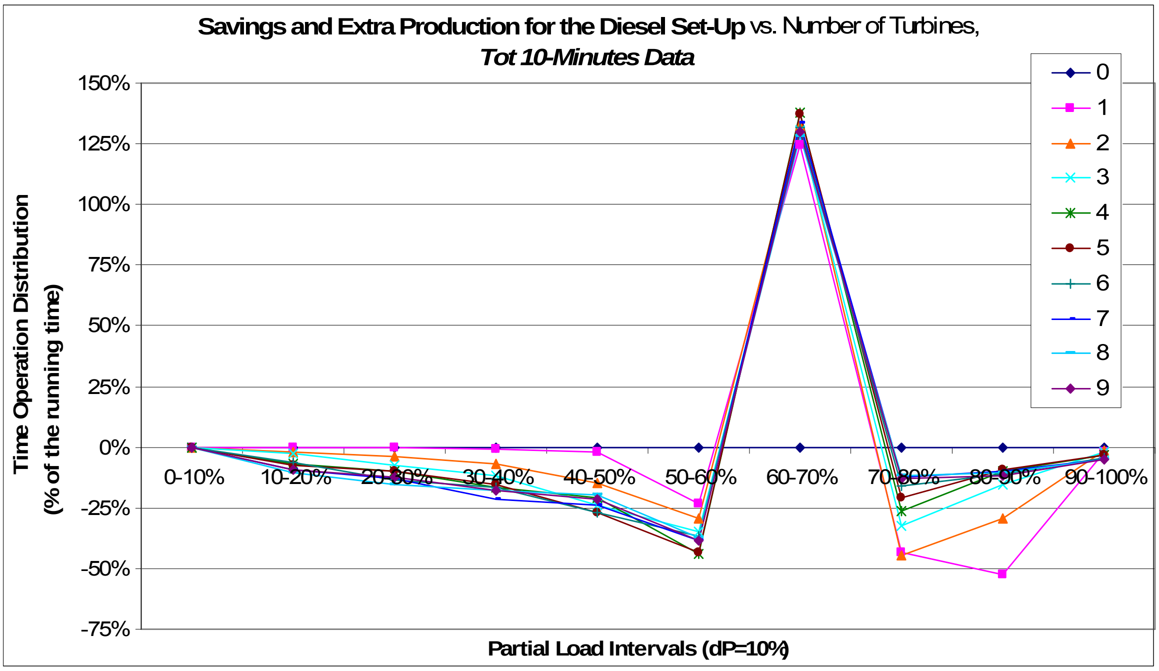


Figure 4-19: Saved and Extra Productions Regarding Diesel Engines Partial Loads Operation for 0 to 9 WT, 10-Minutes Data over the Long Time Period

4.7 Further WD System Regulation with Low Load Diesel

The analyses presented before were reprocessed for the same conditions but with one integrated Low Load Diesel instead of the previous fourth diesel engine. The corresponding results are presented below and compared to the results without LLD.

In the wish to optimise the operation of WD systems at higher wind penetration, the case with one LLD was considered in order to approach a way to improve the power quality by decreasing the negative effect of wind fluctuations on the diesel generators. In this consideration, the results of LLD integration were compiled and compared for two different strategies, both considered with the model (refer to the methodology part 3.4.1 "Low Load Diesel"):

- The diesel genset 4 is always running (Strategy 1)
- The genset 4 is switched off only when its partial load was supposed to be equal to zero in the scenario without low load diesel (Strategy 2)

4.7.1 Wind Penetration and Rejected Energy

With the integration of one LLD the diesel production is higher since the fourth engine runs more often. That is even more important for the strategy 1 since it runs all the time. This influences directly the wind penetration of the system which is 4 % lower than it is without LLD for the strategy 2 and much lower with the strategy 1. This shows that the savings that would be reached with a high wind penetration are much more reduced if the LLD run all the time.

In parallel the rejected energy is influenced in the same proportions: the rejected energy due to the LLD diesel (called “extra LLD” in the figure 4-21) is important at higher wind penetrations linked to the fact that the LLD runs almost all the time at a minimum of 30 % of its capacity.

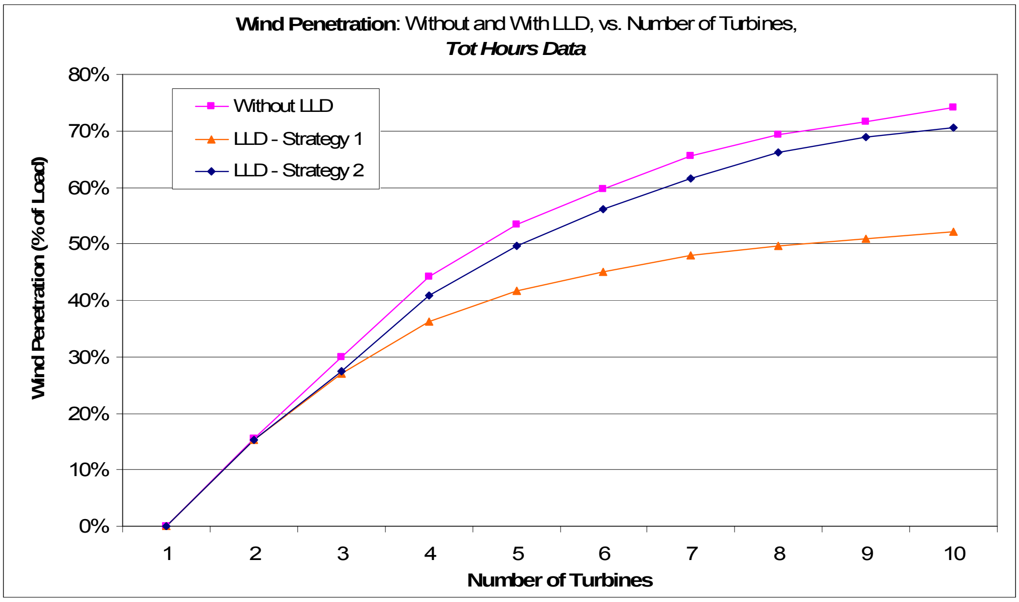


Figure 4-20: Wind Penetration Considering LLD Strategies vs. Number of Turbines, Hourly Data over the Long Time Period

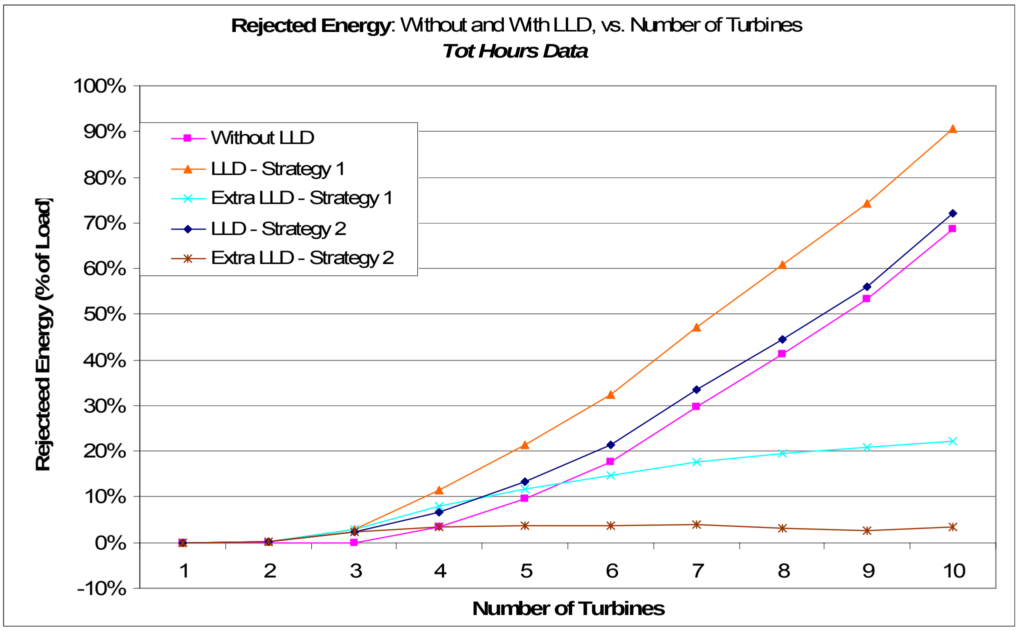


Figure 4-21: Rejected Energy Considering LLD Strategies vs. Number of Turbines, Hourly Data over the Long Time Period

The time scales comparisons give similar results to the ones obtained for the study achieved without LLD. These are given in appendix 9.

4.7.2 Diesel Generators Reaction

Regarding the time of operation of the engines, it could be remarked that the results are similar to the case without LLD, with the particularity that the fourth engine is always on (thus Noff is equal to zero) for the strategy 1. The fourth diesel engine is off during the same time that it was previously (i.e. the Noff is identical) for the strategy 2. The time that the LLD is active was quantified in the model as LLDActifStrat, and the following relation between both strategies was verified:

LLDActifStrat1 = LLDActifStrat2 + Noff

Regarding the number of switching on and off, the same could be remarked for both strategies, since it is directly dependent on the chosen strategies. Regarding the savings could be seen as the difference between the case without LLD and both cases with LLD in the wind penetration and rejected energy curves.

The most interesting results for the consideration of the integration of a LLD is to follow the effect of one integrated LLD on the partial loads distributions of the engines, and particularly on the fourth and the third gensets. Moreover, it is possible to quantify the number of time that the genset is running at low load.

This has shown the possibility and the advantages to adapt the limiting values of the gensets with the LLD case. The engines 4 can run at lower partial loads like it can be used to run only at low partial load. In this case it is therefore easier to adapt the limiting value of the third diesel, which is less stressed by regularly switching on and off. Another advantage is also that the third generator runs less in a large partial loads range.

For the case without integrated LLD, it has to be remembered that the limiting value need to be low for the third genset and that it has the consequence to spread the distribution of its partial loads with resulting similar partial load distributions for the diesel engines 3 and 4. It seems therefore to be interesting to include two low load diesel generators and not only one. This idea should be considered for further WD systems optimisation in parallel to the consideration to adapt further the limiting values of the respective diesel engines. Then, the benefits to integrate LLD in WD systems would be possible to be clearly quantified.

4.8 Effect of Load Variation

Consider a constant load is relevant for an analysis taking into account only the wind fluctuations. Consider a variable load enables to analyse the effect of wind fluctuation coupled to the demand variation on the whole system, and particularly on the diesel reaction. The same results as previous, but for a variable load as input parameter, were processed. They main are presented below and the others are exposed into details in the appendix 11. These will be compared with the previous obtained for a constant load. It results mainly that the diesel operation and reaction to the variations are influenced.

- ***Power Balance Parameters: Wind Penetration, Rejected Power and Diesel Power***

The wind penetration increases while the rejected energy increases too but more significantly. The variation of the results between constant and variable loads is small and regular for the wind penetration and the power to be produced by the diesel engines when the variation of the results concerning the rejected energy increases as a function of the number of the turbines too. This effect of the load variation on the amount of rejected energy has to be therefore carefully considered.

Table 4-4: Constant and Variable Load Comparison for 3, 6 or 9 WT (1, 2 or 3 Groups of 3 WT), 10-Minutes Data over the Long Time Period

	Constant Load			Variable Load		
	3	6	9	3	6	9
Average Wind Penetration	43,71%	64,34%	73,21%	47,40%	67,05%	75,41%
Rejected Power from the Wind	4,02%	31,13%	69,98%	6,68%	39,93%	84,66%
Diesel Power to be Produced	56,29%	35,66%	26,79%	53,44%	33,45%	24,94%

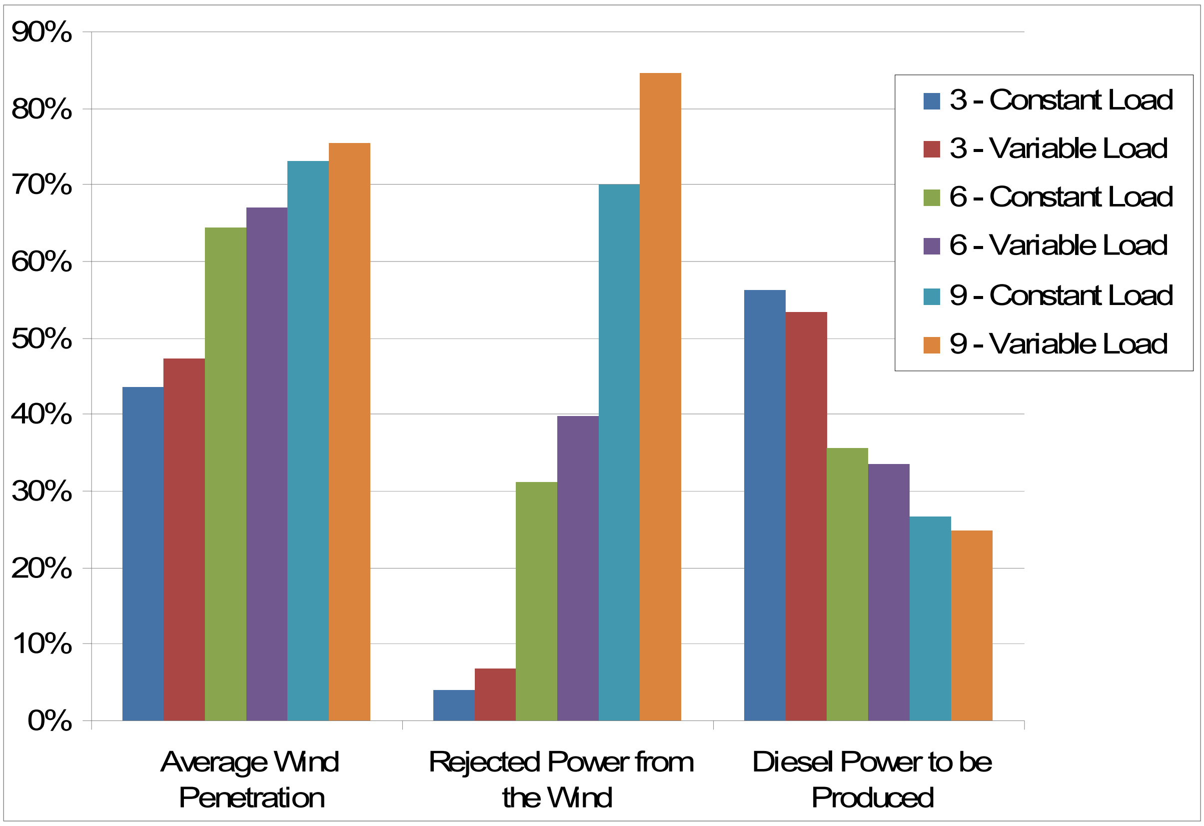


Figure 4-22: Constant and Variable Load Comparison, Chart Representation of the Table 4-4

- ***Running Time***

The diesel gensets running times are quite identical with the particularity that the diesel two runs less.

- ***Number of Switching On***

In opposite to the constant load case, the total number of switching on observed for the whole diesel set-up is not equal to zero although there is no integrated wind power. It means that one of the generators could be sensitive to the load variation and switches on, sometimes or often. For the thesis case study, that corresponds to 8 switching on (and off) of the diesel generator 2.

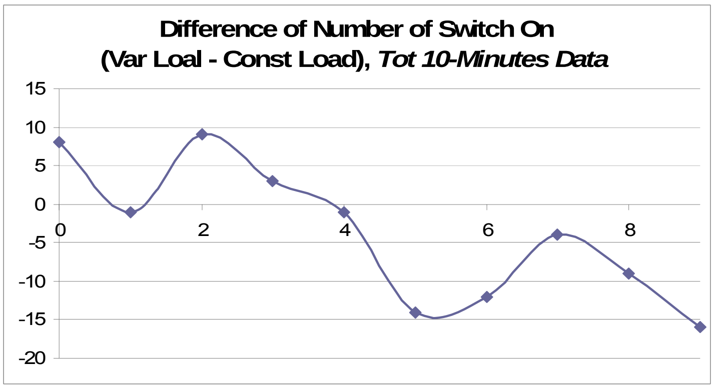


Figure 4-23: Number of Switching On, Difference between Constant and Variable Load Cases vs. Number of Turbines, 10-Minutes Data over the Long Time Period

This gives interesting results with a higher diesel reaction without wind turbine than with one. However it does not vary proportionally to the number of turbines: the variation of the load influences further the whole system and the diesel engines with 6 WT than with 5. That could represent therefore an improvement and could be a reason enough to install 5, 7 or 8 WT and not 6 WT.

The curve presented in the figure 4-23 was plotted for 10-minutes data over the short time period (it is added to the appendix 11). The profile of the curve is similar but the amplitude of the variations of this is ten times smaller. Indeed the number of switching on is much reduced over the short time period.

- ***Partial Loads Operation***

The partial load distribution represented in the figure below is spread in comparison to the distribution obtained for a constant load. The generators are running les at partial loads between 60 and 70%, the second runs at higher partial loads (70 to 80 %) and the third and fourth run further at lower loads**.**

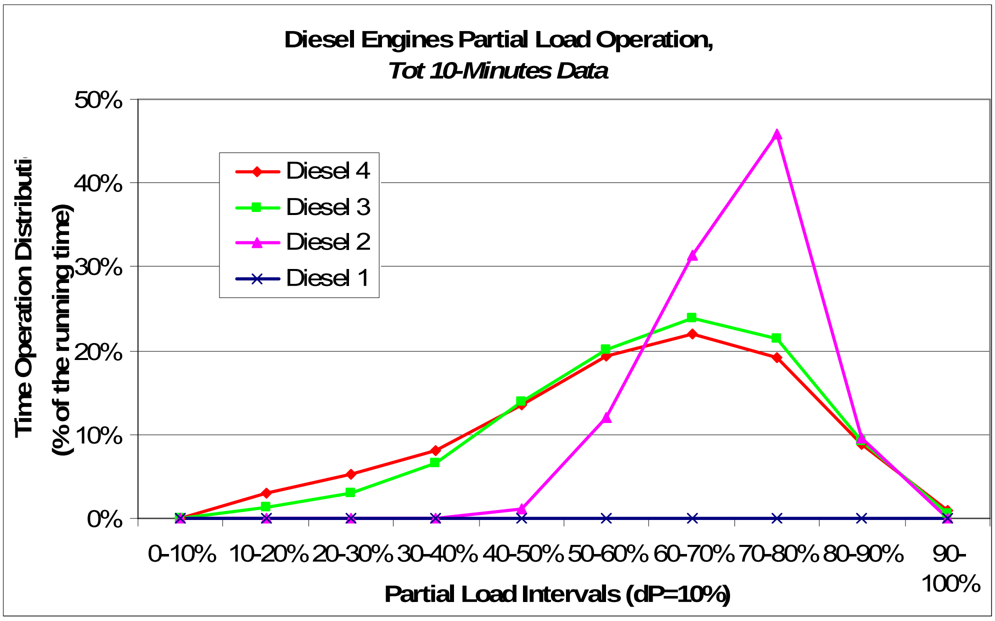


Figure 4-24: Diesel Engines Partial Load Distributions with 3 integrated WT, 10-Minutes Data over the Long Time Period

A comparison of the partial loads distributions obtained for 3 WT between the different time scales, i.e. pie charts for Tot 10-minutes data, dt 10-minutes data and dt 10-seconds data, was added to the appendix.

- ***Savings and Extra Productions***

The energy saved for the whole system with the integration of wind energy is higher for lower numbers and turbines and reduced for higher numbers. The amount of saved energy approaches 77 % with a variable like with a constant load. The specificity of the curve corresponding to a variable load case (figure 4-25) is that there is no extra production for 1 WT.

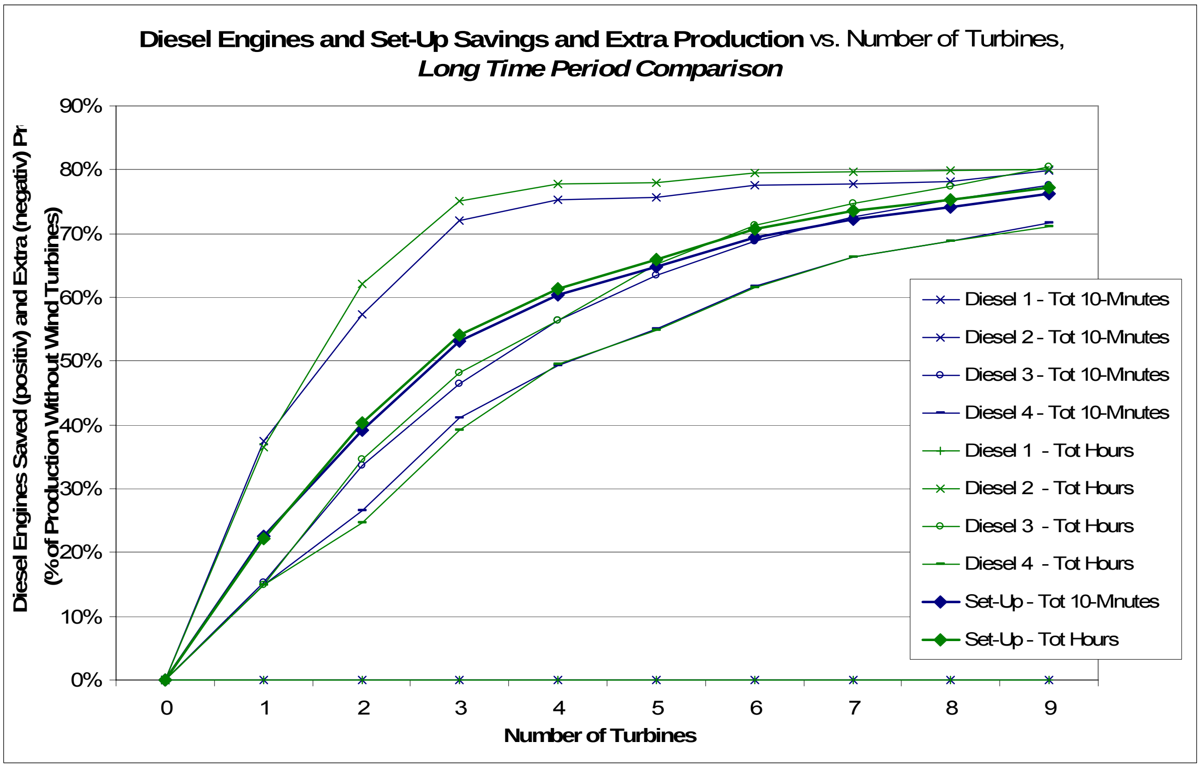


Figure 4-25*:* Diesel Engines and Set-Up Saved and Extra Productions vs. Number of Turbines, Time Scales Comparison over the Long Time Period

Concerning the partial loads, the distributions of the saved and extra produced power is even more significantly influenced by the variation of the load than the previous: these are further spread. The results for the long time period show a clearer effect while this is reduced for the short time period (i.e. the profile of the distribution are more similar to the previous obtained for a constant load).

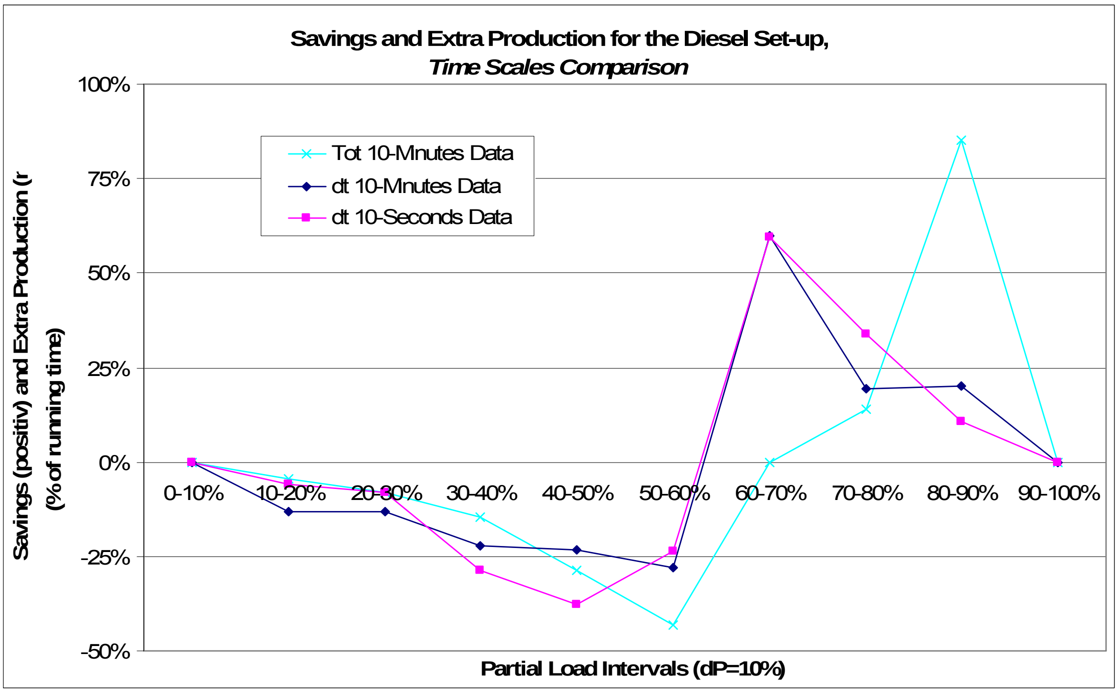


Figure 4-26: Saved and Extra Productions Regarding Diesel Engines Partial Loads Operation for the Diesel Set-Up with 3 WT, Time Scales Comparison over the Short and Long Time Periods

The effect of an increasing number of turbines, on the general profile of the curve corresponding to 10-minutes data over the long time period (figure4-26), is similar to the effect observed for a constant load (see paragraph "Results – Expected Saving – Diesel Operation").

4.9 Sensitivity Analysis

The three characteristics chosen for the sensitivity analysis: level of the load, size of the diesel gensets and limiting values of partial loads are all inter-dependent. They are related to the power system design. It will be shown with this part that the model can be used to optimise the previously designed power system, in consideration that, if one of these characteristics changes, the effect on the diesel reaction should be considered and then the other could be adapted. With a reiteration of the calculations after a change of one of these an optimal design could be found.

4.9.1 Level of the Demand

Change the demand is equivalent to change the ratio between the demand and the produced wind power, i.e. the wind penetration. A higher demand with smaller wind turbines would correspond to a better grouping effect, and therefore a better diesel generators reaction.

As it was stated just before, change the demand would result to the need to adapt the size of the diesel engines and the limiting values. Since all are dependant and the level of the demand would be fixed in feasibility studies, it is not of first importance to study the effect of a change of the demand on the modelling. The two following point are much more important to be considered in order to study the sensitivity of the model results.

4.9.2 Size of Diesel Engines

The diesel generators capacity should be carefully chosen. The model should be process with a first capacity and then this can be adapted with respect of the diesel operation results (calculated partial loads and number of switching on during operation) like it is presented below.

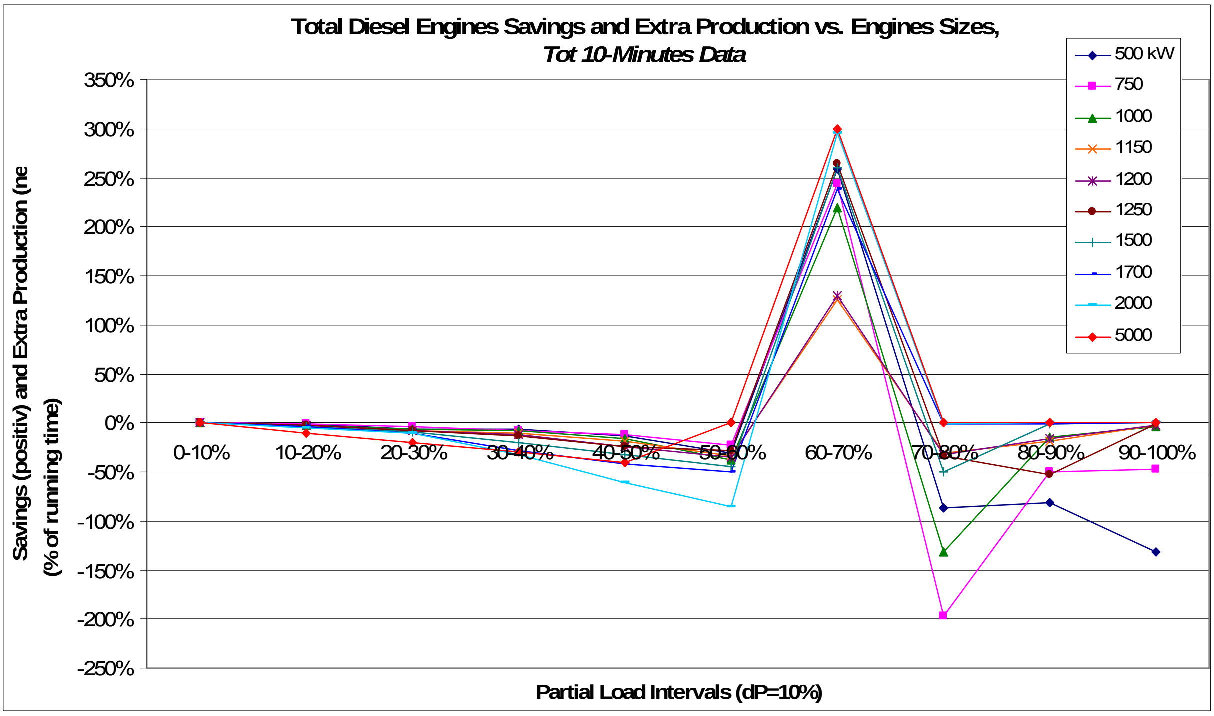


Figure 4-27: Saved and Extra Productions Regarding Diesel Engines Partial Loads Operation for different Engines Sizes with 3WT, 10-Minutes Data over the Long Time Period

The curve above is the estimation of the saved and extra production for varying size of the generators. From this curve, tricky diesel sizes were chosen, such as 1,150 and 1,250 kW (just close to the chosen size for the study presented in this report) to show how the size can be optimised. And to show the sensitivity of the results to the size of the engine very small or big diesel generators were studied (750 and 5,000 kW). It can be concluded that:

- With smaller engines, the partial load distribution of these would be translated on the right, what is positive because they will run less at low partial loads, but the diesel generators stress would be higher: they will be often overloaded, and moreover, they will obviously switch on and off more easily in response to wind fluctuations. Therefore the risk incurred to use smaller diesel gensets that it should be will result to more disconnections of the whole grid.
- With bigger engines, they will react less to wind penetration (switch on and off less time, even if they will accelerate and decelerate during their operation), but they will also run at lower partial loads. The distribution of their partial loads was plotted and it results that only the fourth genset is running under 60%, which confirm the previous remarks.

Regarding the savings and extra production for 1,150 and 1,250 kW, it can be observed that the partial load distribution is more spread for 1,250 kW in comparison to the results for 1,200 kW. Indeed, if the diesel gensets are running less at partial loads between 50 and 60%, that means that it is running more at other ranges of partial loads.

The diesel reaction for the long time period corresponding to 1,150 and 1,250 kW diesel engines size was studied. That enables to follow the derivation or not of the results in comparison to the chosen diesel size. These results are presented below, and the same results for 750 and 5,000 kW were added to the appendices (appendix 10), in order to validate the statements given above.

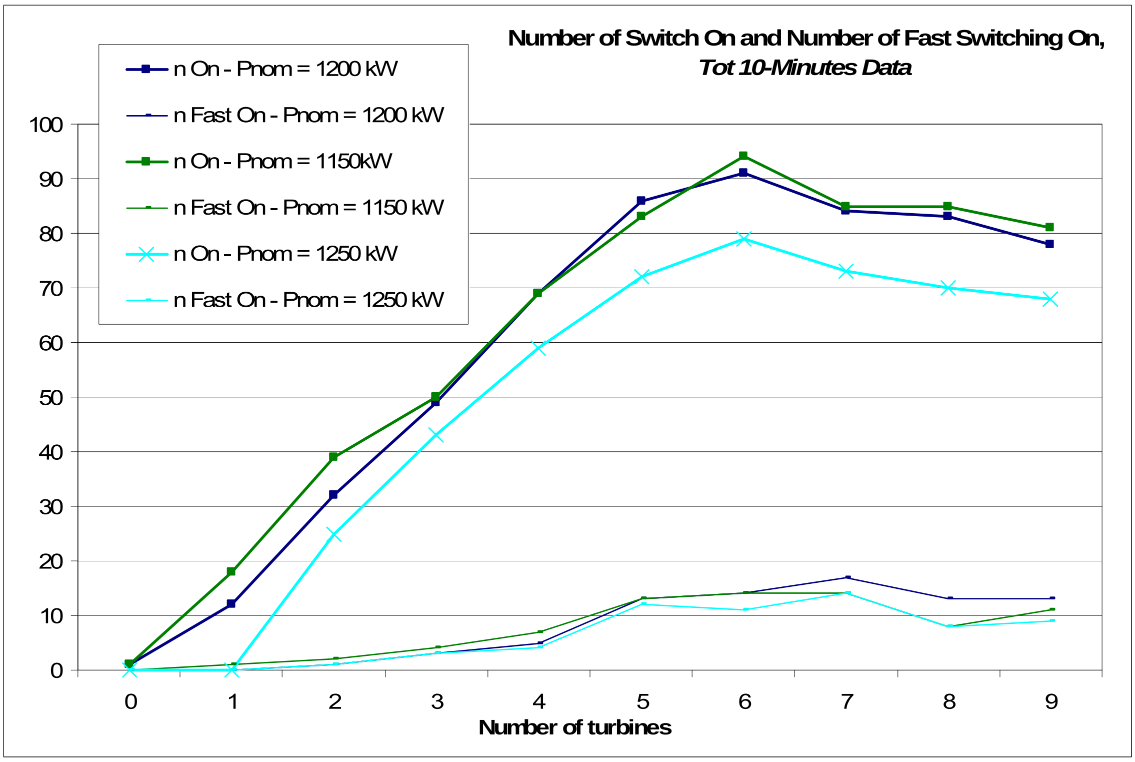


Figure 4-28: Number of Switching On and Fast Switching On for the whole Diesel Set-Up, 10-Minutes Data over the Long Time Period

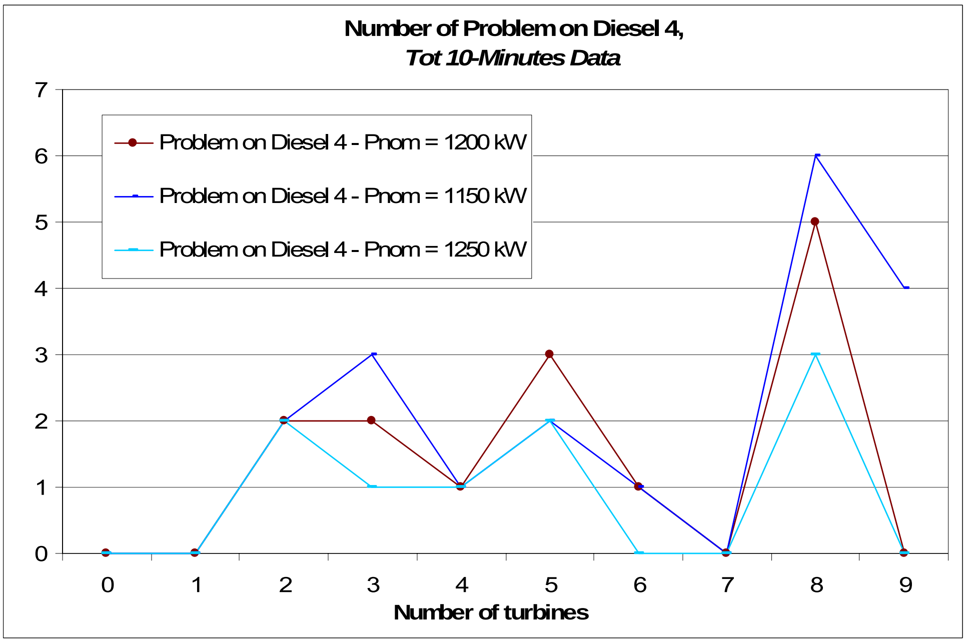


Figure 4-29: Number of Switching On of the Fourth Engine, 10-Minutes Data over the Long Time Period

It results that:

- With a nominal power of the diesel generators of 1,150 kW, the diesel reaction is similar, but the number of times that a problem on the diesel genset 4 occurs is higher.
- With a nominal power of 1,250 kW the effect of the wind fluctuations is reduced: number of switching on and number of problem lower.

As remark, it was observed with the model, that the decrease or increase of the effect is mainly linked to the second diesel: this genset is not any more requested with a nominal power of 1,250 kW, while is further requested with 1,150 kW.

In addition to the savings and extra production regarding partial loads, it could be therefore interesting to enlarge a little the diesel capacity in comparison to what were done.

In conclusion, adapted size should be chosen in consideration to what were presented in this report. And then, a combination of different sizes should be considered because it can be a good strategy, such as the combination of a small diesel for low load operation, while the instantaneous wind penetration is high in the system, and a large diesel, which would run when there is almost no wind. It seems that this strategy was currently not developed, since identical sizes of engines are in general installed.

4.9.3 Limiting Partial Load Values

Diesel reaction parameters should be adapted in order to minimise the effect of switching on and off on the diesel generators. That could be achieved with the model for a defined number of turbines, i.e. for a certain wind penetration. They should and could be carefully determined in order to find the most suitable parameters to every special case study.

The repartition of the partial loads distribution helps to choose the right limiting values since it was shown that this distribution is directly dependent on these limiting values. Then the number of switching on can be plotted as function of the limiting values to switch off the gensets. It is therefore possible to obtain the effect of one of these limiting values, but the resulting curves depend on the other limiting values which should be kept fixed. For remembering, the Off limiting values were chosen in the first power system design equal to 80% (Off 1 Limit), 50% (Off 2 Limit) and 20% (Off 3 Limit). The two figures 4-30 and 4-31 show the influence of a change of Off 2 and 3 Limits.

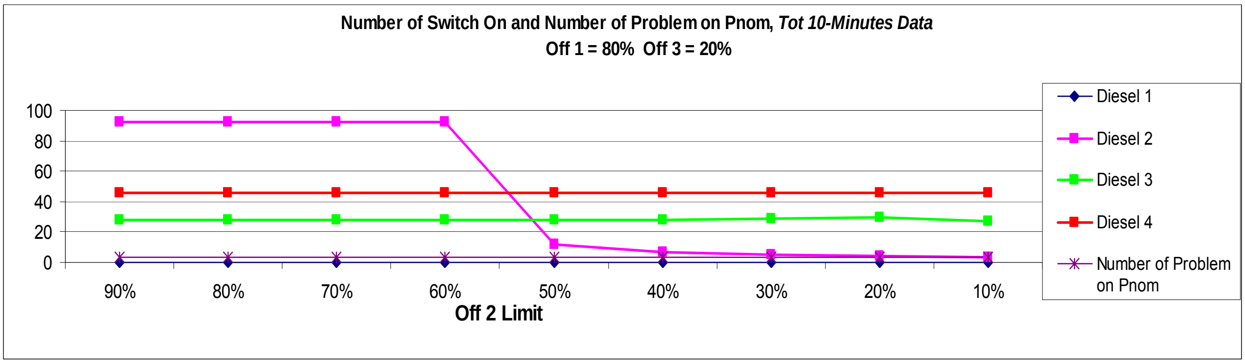


Figure 4-30: Number of Switching On function of Off 2 Limiting Value with 5WT, 10-Minutes Data over the Long Time Period

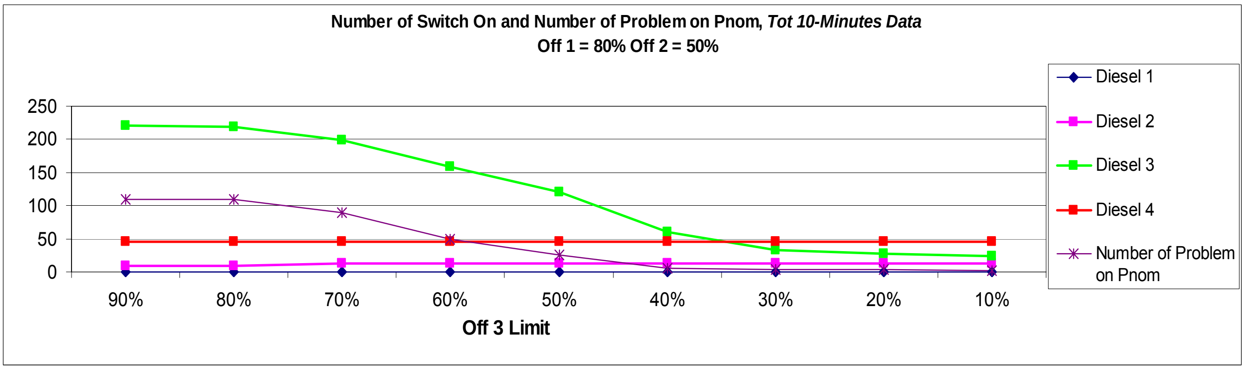


Figure 4-31: Number of Switching On function of Off 3 Limiting Value with 5WT, 10-Minutes Data over the Long Time Period

It seems therefore that Off 3 Limit could be 30 % without influencing the diesel generators reaction. This limit should be entered in the model and the curve of the number of switching on for a variable Off 2 limit (figure 4-30) should be plotted again and show how the diesel set-up would be influenced. Then, the number of switching on should be consulted to see the real effect for a variable number of turbines. Indeed, the numbers of switching on represented in the two figures above correspond to 3 WT. Off 3 could be increased for 3 WT to 30% but the effect of this parameter will not be the same for a higher number of turbines.

The off limiting values should be carefully used and fixed in consideration of their influence on the number of switching on and the distribution of partial loads. They can be adapted then for a chosen number of turbines, i.e. with a number of turbines which was already approached as a good compromise.

The variation of the partial loads between on and off limiting values should be limited but enough enlarged to avoid fast switching on and off, but these limiting values should be enough far from the limits of partial loads operation (0% for On limits and 100% for Off limits) in order to avoid negative and over 100% partial load results, which corresponds to a fault of the system.

5 CONCLUSION

5.1 Concluding Remarks

The model can be used to optimise WD system in respect to the power system design (gensets size, number and their limiting values) and the number of turbines to be integrated.

The effect of wind fluctuations is significantly more important on diesel generators reaction than on wind penetration and rejected energy. At high wind penetration, the wind fluctuations have definitively an important effect on diesel engines operation. This is significantly decreased with low load diesel. The results show that a WD system can not be efficient with a dump load device only, other equipment related to the respective strategies must be integrated.

The results obtained with the model presented in this thesis should be considered as a part of a general WD systems design studies, which should additionally take into consideration an economic analysis and a deeper power quality assessment.

5.2 Suggestions for Further Work

5.2.1 Future Model Usage

The electrical output of many wind turbines can be assessed with other software such as Wind Pro, and used as input data in the model. It should be remembered for the choice of the wind turbines technology, that several smaller turbines in diverse locations would decrease the variability of the overall output wind power, but also that they should be indirectly connected to the grid and composed of synchronous generators.

The input data could be composed of successive values (i.e. full table) or not. The model should just be carefully calibrated in this consideration. The determination of the right number of turbines could then be achieved. Every time scales can be used to determine the power flows, but 10-minutes or 10-seconds data are warmly recommended. The study should be assessed, at least for few days, at a small time scale to see the real effect on the diesel generators.

The model can be used to design wind diesel systems from a large time interval. Then, it could be used in order to optimise the first design, i.e. the diesel generators capacity and their limiting partial loads values. Then, it could be used to optimise the integration of wind power, regarding the number and type of turbines, in the consideration of possible restrictions such as an acceptable percentage of rejected energy, but also an acceptable number of switching on and off that could support a diesel genset during a certain period (remark: the range of partial load that can support the engines could be request to the constructor).

5.2.2 Other Strategies to Consider

Additional strategy to low load diesel should be modelled as an extension part of the model, in order to figure out the real effect of these strategies on the savings and particularly on the diesel generators operation. Valuable benefits would be then useful for an economic analysis.

With this thesis, good strategies were underlined, they consist to include a low load diesel or batteries, or to force the diesel generators to run at higher and constant partial load than they should operate and dump the excess of produced energy.

Nowadays, the previously named strategies are still at a development stage or are linked to high investment costs. They will be hopefully further developed during the next years in the wish to promote renewable energies. This will amongst other things able to sustain further more the remote areas by reducing their dependence to fuel supplying requirements.

5.3 Discussion on Sustainability

The general orientation of this final part will be to discuss the potential and the interest to increase the use of wind power technology in isolated grids in regards of the sustainable development. This will give an idea about the ability to develop WD systems in developing countries.

Wind energy has a growing importance world wide. There is a promising potential of development considering all the possibilities to install wind turbines on-grid and off-grid. In stand-alone system, the challenge to replace conventional power sources by wind power is high due to integration difficulties, but the savings justify the wish to take up this challenge. Even if the savings are estimated as small for one WD systems, they are not insignificant, and should be considered at a large scale of WD systems development. Moreover, most of the diesel generators are noisy, consuming devices and they linked to possible risk of spills (spreading and leakage) on the ground can have the negative effect to pollute the ground water, which is most of the times in these remote locations the water supply of the local population.

The WD systems implementation would reduce fuel usage at the source and the dependence of remote areas of fuel supply and prices, which tendency increase, but will also reduce greenhouse gases emissions. This environmental consideration is an important factor of renewable energies development in the current evolution towards carbon savings and Clean Development Mechanisms. The current concern about global warming therefore incites to develop renewable and clean energies in these locations. There is therefore a proven interest to improve and enlarge the use of WD systems.

Further wind turbines installed in those remote areas like in developing countries would be a proof of the benefits of harnessing the wind: the savings would be better, and the project would be even more interesting if the wind penetration of the installed WD systems is maximised. The integration of wind energy should and could nowadays be carefully assessed with detailed studies in consideration that the output power fluctuations are significantly higher for wind turbines than for all other technologies. Additional devices for diverse strategies, power electronics and adapted controllers should therefore be efficiently integrated in order to ensure a robust system.

It could be also considered to diversify sources in WD system by the integration of solar, as example. Like that the seasonal variability of the resource could be use to provide energy with wind or solar in respect to the availability to these two different sources. The combination of both could also decrease the variability of the power feed in the grid like it was underlined with the possible great effect of turbines and wind parks grouping. However, advances and complicated systems with high level of requirements could be another barrier due to high investment costs. Other requirements for maintenance, monitoring preferably by local people, and repair parts would justify the choice of simpler systems with standard components, facilitated layout, etc. Hybrid systems should be implemented but not complicated for these reasons. They should before all respond to local needs and possibilities. Once more, it could be understand that WD systems with high wind penetration would be better than complex systems including many renewable energy sources.

In conclusion, even if the wind resource is freely supplied by the nature, even if it is enable to avoid the use of conventional fuels, to decrease the costs of operation and the emissions, and finally to respond to a large need in remote areas and thus to support remote communities, there are some non-negligible barriers: the variability of this non-predictable resource, the high investment costs, the current width of high wind penetration systems, the non-availability of maintenance and operation monitoring (particularly more important for high wind penetration systems), and also most of the times the length of procedures in order to develop such tricky projects.

To face the lack of maintenance and repair part, it is necessary to develop local abilities in order to ensure a sustainable system. It is possible to organise formations for knowledge transfer to these locations, even if the wind turbines are in general directly exported and not especially developed for local market, which comforts the trend of high prices.

Then, to face the problem of wind variability studies like this thesis will bring further solutions. Good strategies would be further developed and installed, with adapted programme approaches and prototypes to prove the benefits of installing such systems. These should be promoted in developed and developing countries in order to justify their interest worldwide, before installing them in remote areas, because people there could feel that it is impose to them since it is not something already proven and used in developed countries.

It should be always remember that the development of a region is linked to the access of technology and thus of energy. There is therefore a need to minimise the cost of electricity. At the moment, wind energy is still an expensive technology regarding investment, but it is the same for everything which is sustainable. In the future it can be hopped that the trend will be reverse.

6 ABBREVIATIONS

AC / DC	Alternating Current / Direct Current
CDM	Clean Development Mechanism
kW	Kilowatt (measure of power)
LI	Lahmeyer International GmbH
LLD	Low Load Diesel
MVA	Mega Volt-Ampere (measure of apparent power in an AC circuit, it is dimensionally equivalent to a watts capability)
MWh	Mega Watt-hours (measure of energy)
VAR	Volt-Amperes Reactive (measure of reactive power)
WD	Wind Diesel
WT	Wind Turbine

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[9] « Electrical Integration of Renewables » ; Murray THOMSON, Module Director ; Master Programme of Renewable Energy Systems Technology ; CREST ; 2004.

Technical Information about Strategies:

- Wind Turbines: GE Wind, http://www.gepower.com/businesses/ge_wind_energy/en/index.htm
- Smaller WT and WD Systems Applications: Enercon, http://www.enercon.fr/en/_home.htm ; Vergnet, http://vergnet.comfi.org
- Dump Load Devices: WidOhm Mat, Engines and Technical Facilities, www.m-a-t.de
- Batteries: Saft, http://www.saftbatteries.com ; SMA, http://www.batteriesma.com ; Merlin, www.merlin.equipment.com
- Flywheel: Regenerative Power & Motion, http://www.geocities.com/infotaxi/schwung-grundlg.htm

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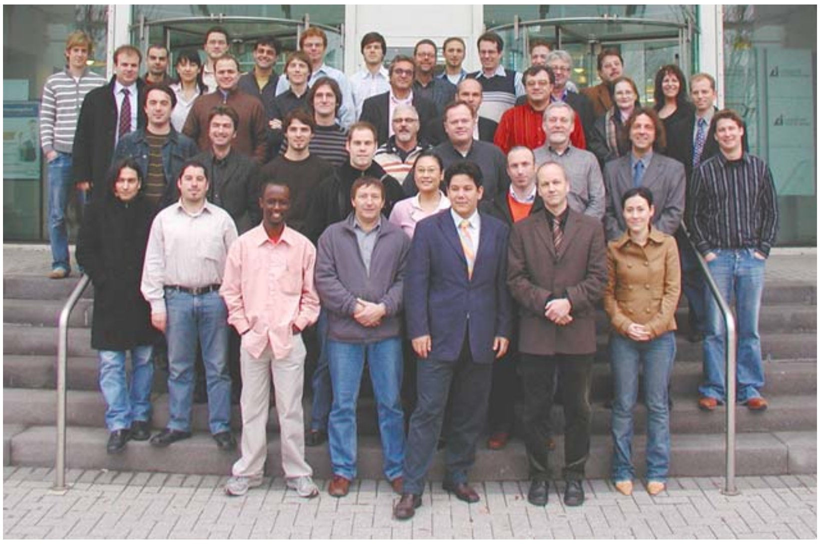
Frank Umbach, Vladimir Kremenetskiy , Richard Lawless, Mathieu Sarran, Elena Moreira Lator,
Julia Höpp, Cristina Manalo, and Patricia Recio Rios.*



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9 LISTS OF FIGURES AND TABLES

9.1 Figures

9.2 Tables

10 APPENDICES

Appendix 1: Presentation of Lahmeyer International GmbH

From	"Lahmeyer & Co" founded by Wilhelm Lahmeyer in 1890
Founded	1966 in Frankfurt am Main
Headquarters	Bad Vilbel, Germany
Services	Management and Engineering Consultancy
LI Group	12 Subsidiaries
Employees	LI group: 800; LI: 450
Annual Turnover	LI group: 104 million Euro; LI: 83 million Euro
Representatives	in 50 Countries
Projects	in 140 Countries world-wide

Lahmeyer International is recognised as an independent firm of consultants by all major international institutions.

LI Infrastructure

- Energy
- Hydropower and Water Resources
- Environment Technology
- Transportation

*Lahmeyer International is one of the leading companies world-wide that can offer the **complete spectrum** of engineering services with all associated disciplines. The services are related to studies, planning and execution.*

Seven Operating Departments in the Energy Division

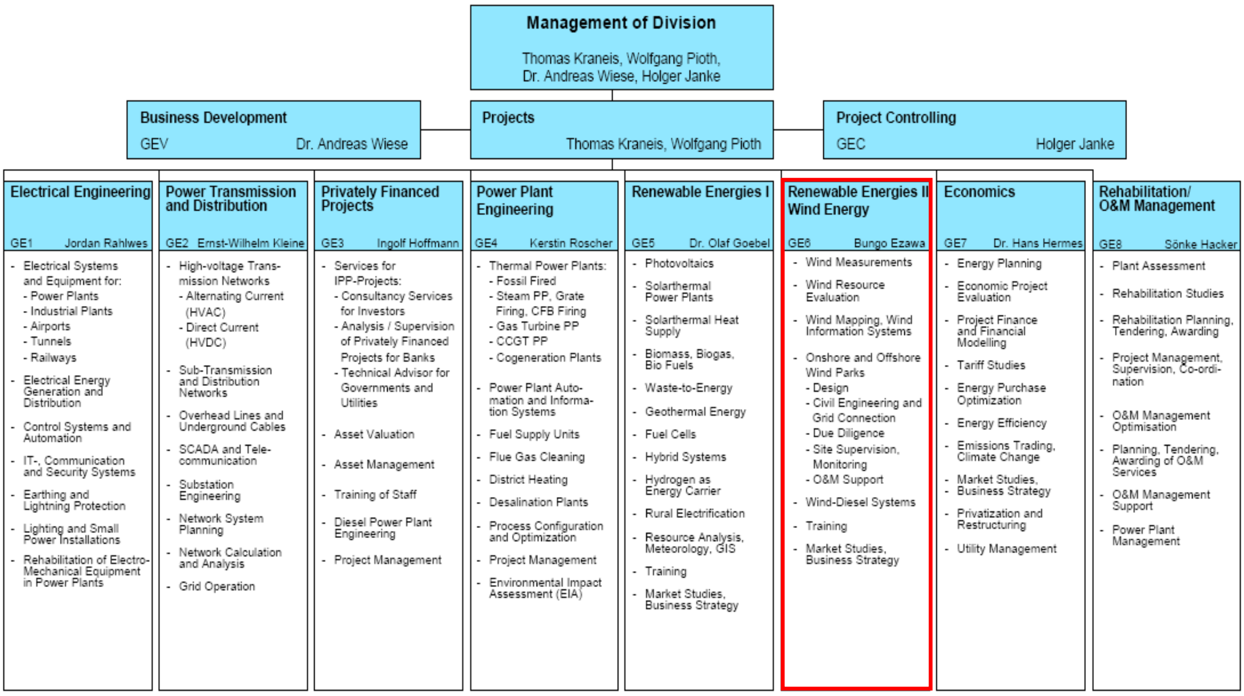


Figure: Organisational Structure of Lahmeyer International's Energy Division

Wind Energy Department: A wide range of valuable products and services

- ***Study of Resources:***
- Renewable potential analysis
- Measurements and analysis of meteorological data
- Wind mapping, wind information systems
- Site selection

- ***Studies for Projects:***
- Pre-feasibility studies, feasibility studies, due diligence studies, economic analysis
- Environmental Impact Assessments; e.g. for wind parks: noise emission, disco effects, visualisation, animation, ornithological surveys

- ***Planning and Engineering:***
- Conceptual design
- Micrositing for wind parks
- System planning of PV integration in parallel operation with existing hydropower plants
- Solar thermal electricity generation: Specialised on integration of solar heat in combined cycles
- Hybrid System Planning

- ***Project Implementation:***
- Tender Procedures
- Factory inspections, acceptance tests
- Erection, commissioning supervision
- O&M supervision

- ***Cross Topics:***
- Rural electrification, solar home systems
- Technical support emission trading and certification
- Life cycle analysis of renewable energy projects

The experience generates the success

Key references
- More than 150 measurements masts installed
- Country wide wind mapping based on KLIMM for 8 countries
- Wind potential evaluation for more than 190 wind farms
- KLIMM studies for more than 40 wind farms
- Feasibility studies for more than 40 wind farms (2,200 MW)
- Due diligence studies for more than 150 wind farms (2,300 MW)
- Construction supervision for more than 30 wind farms (750 MW)
- O&M supervision for more than 60 wind farms (1350 MW)

With energy projects in more than 32 countries, the Wind Energy department of Lahmeyer International has gained experience in complex terrain, multicultural environments and diverse markets.

Appendix 2: Cross Matrix of Stress Factors and Damage Mechanisms to Consider for Battery Unit Design in the Aim to Enlarge Batteries Lifetime

Source: "Development of Battery Lifetime Models for Energy Storage Systems in Renewable Energy Systems", Paper presented at STORE Conference the 20-22th Octobre 2003 in Aix en Provence (France).

	DAMAGE MECHANISMS				
STRESS FACTORS	Corrosion of the positive grid	Sulphatation	Shedding	Loss of water	AM degradation (Loss of charged active material surface)
Temperature	Strong impact, positive correlation	High temperature has negative impact at low SOC high temperature has positive impact during full charging	No direct impact	Increasing with increasing temperature	Low impact with high temperature on neg. electrode expanders
Depth of discharge	No direct impact	No direct impact	Strong impact	No impact	Direct impact
Acid stratification	Impact through low acid concentration in upper part of electrode	Strong impact through inhomogeneous current distribution and local SOC	Indirect through increase gassing indirect through strong sulphatation in the lower part if the electrode	Indirect through extended charging periods at high voltage	Impact through inhomogeneous current distribution and SOC
Discharge rate	Indirect through positive electrode potential	High discharge rate create many and small sulphate inhomogeneous current distribution causes in. SOC	Probably increased shedding due to high DOD on outer array of active material [pasted plates]	None	Increases inner resistance due to AOS-model (agglomerate of sphere)
Charge rate	Indirect through positive electrode potential	No impact	No impact	Indirect through higher voltage & higher temperature	Positive impact through smaller crystals
Time at low states of charge	Indirect through low acid concentration and low potentials	strong impact	No direct impact	None	None
Cycle duration	No direct impact	Strong impact	No direct impact	No direct impact	None
Voltage	High impact according to corrosion rate as a function of potential	Positive impact at high voltages	No direct impact	No direct impact	Strong impact during voltage reversal (mainly neg. Electrode)
Acid concentration	Strong impact Low concentration --> high corrosion	Strong impact Low concentration --> high solubility of $Pb2+$	No direct impact	No direct impact	No direct impact
Ah throughput (Overall charge transfer)	No impact	No direct impact	Impact through mechanical stress	No direct impact	Loss of active material structure, larger crystals
Ripple current ($f > 1$ Hz), without zero-line crossing of current	Impact through potential variations (depends on frequency)	No impact	No direct impact	Some impact at high states of charge	Indirect through higher temperature
Partial cycles ($f > 1$ Hz)	Impact through potential variations (depends on frequency)	Increase size of sulphate crystals	No direct impact	No impact	Impact
Gas evolution rate	No impact	Indirect through reduced charge efficiency	Strong impact	Strong impact	No direct impact
Reverse charging	No significant impact	Indirect	Very strong mechanical stress	Small impact	Strong loss of negative material structure through loss of expanders
Charge factor	No direct impact	Positive impact through regimes with high charge factor	Strong impact through gassing	Strong impact	No direct impact

Appendix 3: Types of Battery, Lead-Acid or Nickel-Cadnium, Advantages and Disadvantages, Effect of the Temperature on the Lifetime

Table: Advantages and Disadvantages (source: "Batteries and Charge Control in Photovoltaic Systems" ; James P. DUNLOP ; Florida Solar Energy Center, 15/01/1997).

Battery Type	Advantages	Disadvantages
Flooded Lead-Acid		
Lead-Antimony	low cost, wide availability, good deep cycle and high temperature performance, can replenish electrolyte	high water loss and maintenance
Lead-Calcium Open Vent	low cost, wide availability, low water loss, can replenish electrolyte	poor deep cycle performance, intolerant to high temperatures and overcharge
Lead-Calcium Sealed Vent	low cost, wide availability, low water loss	poor deep cycle performance, intolerant to high temperatures and overcharge, can not replenish electrolyte
Lead Antimony/Calcium Hybrid	medium cost, low water loss	limited availability, potential for stratification
Captive Electrolyte Lead-Acid		
Gelled	medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
Absorbed Glass Mat	medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
Nickel-Cadmium		
Sealed Sintered-Plate	wide availability, excellent low and high temperature performance, maintenance free	only available in low capacities, high cost, suffer from 'memory' effect
Flooded Pocket-Plate	excellent deep cycle and low and high temperature performance, tolerance to overcharge	limited availability, high cost, water additions required

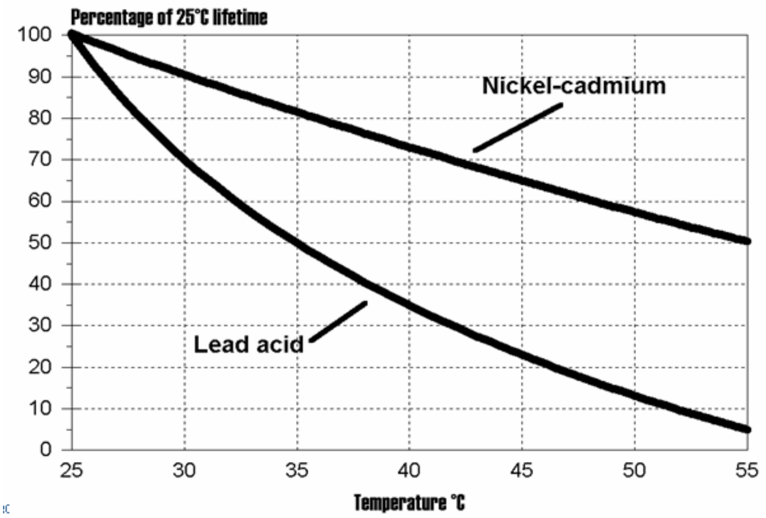


Figure: Effect of the Temperature on the Percentage of Battery Lifetime Calculated at 25°C (source: Saft Presentation at Lahmeyer, 20/01/2004)

Appendix 4: Model's Input Data Presentation, Variation of a Single or Group of Turbines, 10-Minutes Data over the Long Time Period

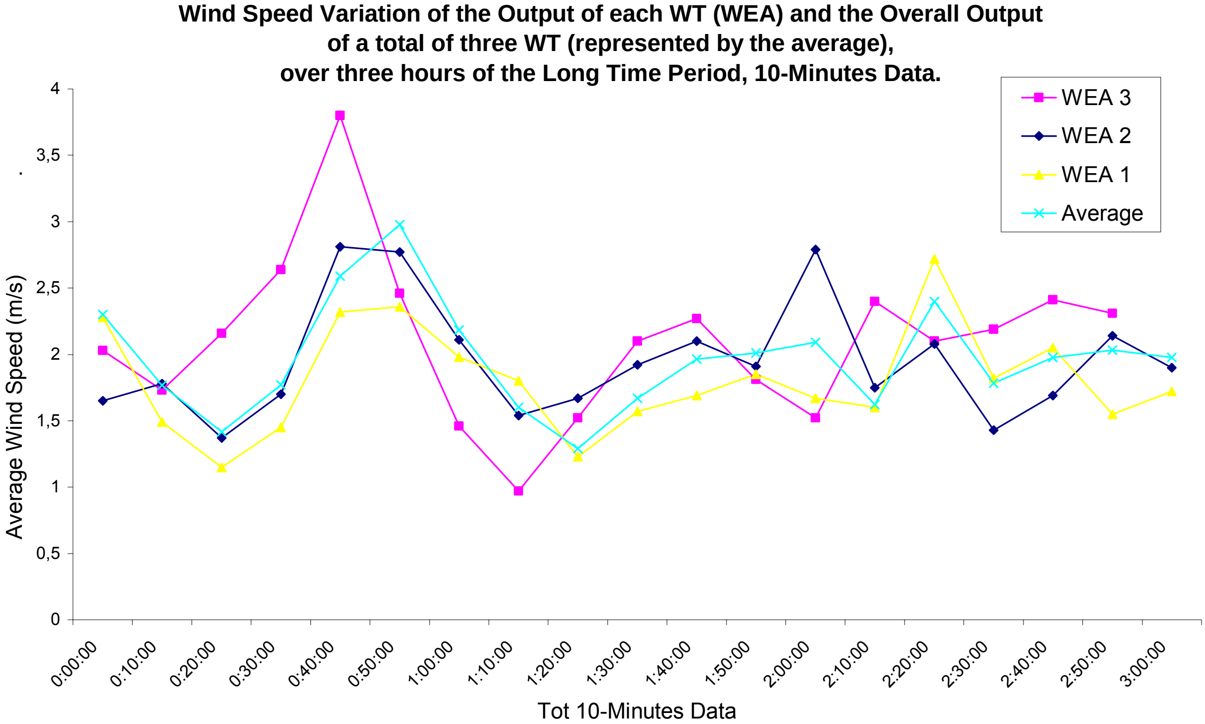


Figure: Wind Speed Variation at each WT Used as Input Data in the Model,
10-Minutes Data over the Long Time Period during 3 Hours

The figure above shows the variation of the wind speed from one turbine to another and shows also the effect of grouping with the average of these values. This average curve has smoother variations for a group than for one single WT. The same curve plotted with electrical output data has given the same observation.

The two figures below show the effect of wind variations and the effect of grouping on the delivered electrical power. The amplitude of the overall variations underlines that the electrical output power varies more and faster for a group during high production time. At low regime of wind, the output power is reduced for a group as it is for a single.

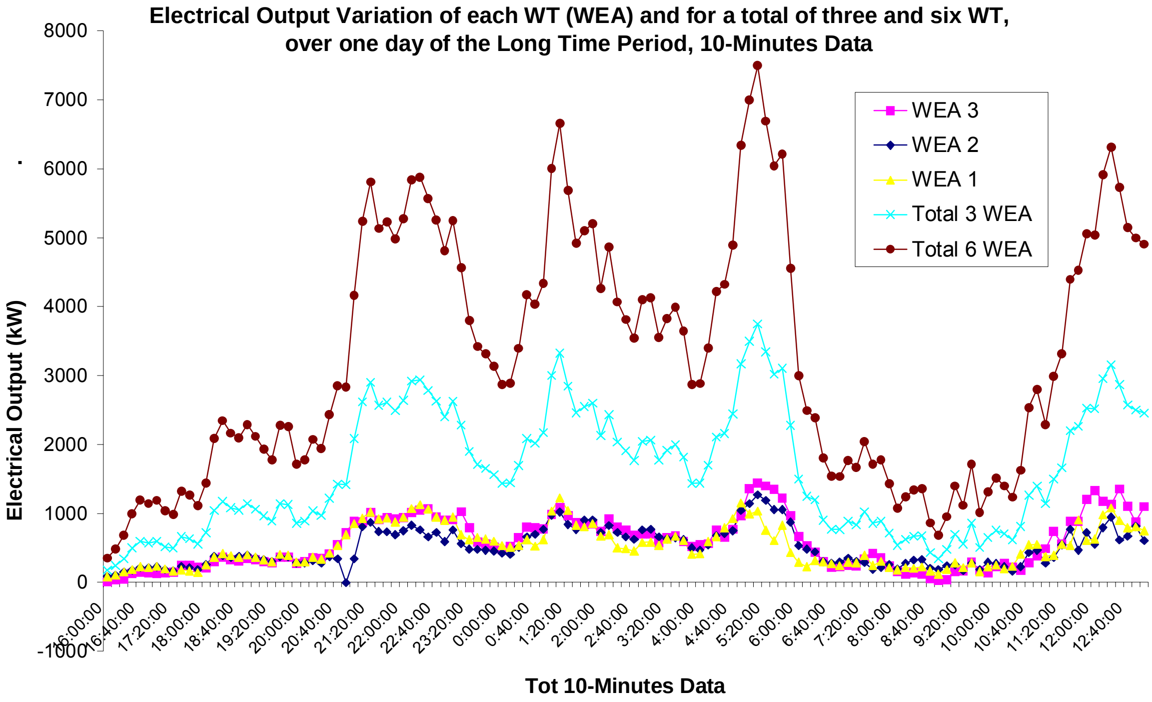


Figure: Electrical Output Variation at each WT Used as Input Data, and Electrical Output Variation for 1 and 2 Modelled Groups of 3 WT, 10-Minutes Data over the Long Time Period during 8 Hours

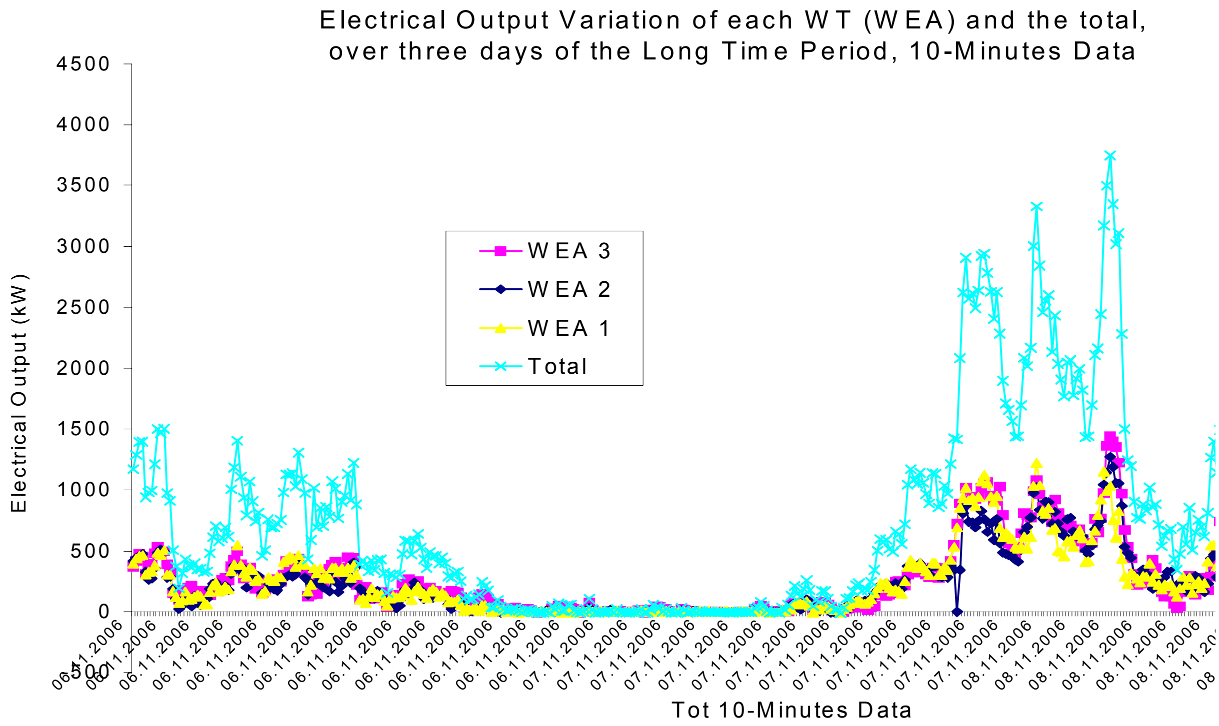


Figure: Electrical Output Variation at each WT Used as Input Data, and Electrical Output Variation for a Group of these 3 WT, 10-Minutes Data over the Long Time Period during 2 Days

Appendix 5: Model's Procedure of Usage Presentation

	Time Intervals	Corresponding Excel Sheet
Input Data		
Wind data at every time scale (full raw of values or not)	All Time Intervals and Time Scales	Input Sec/Min data
Variable Demand Data defined for corresponding time scale(s)		VarLoad
Data Calibration	All Time Intervals and Time Scales	Calib
Calculation Procedure		
Definir Variable load or not and level		
Init Study Time Base at 0		
Vary nTurbines 0 to 9		
Vary Study Time Base 0 to 1		
Vary nTurbines 0 to 9	All Time Intervals and Time Scales	To be operated in Excess&WindP
Vary Study Time Base 1 to 2		
Vary nTurbines 0 to 9		
...		
Vary Study Time Base 3 to 4		
Vary nTurbines 0 to 9		
Results for Comparisons (Time Scales & WD System or non-retrofited diesel system) **for Variable n of Turbines:**		
Wind Penetration & Rejected Energy	All Time Intervals and Time Scales	Excess&WindP
Number of Switching On anf Off (in long or short term)	All Time Intervals and Time Scales	DeP
Diesel Engines and Set-up Partial Loads: Distributions, Savings and Extra Production	Tot min, dt min, dt sec	Partial Loads
Diesel Set-up Production	All Time Intervals and Time Scales	Savings

Study Time Base	0 Tot minutes 1 Tot hours 2 dt minutes 3 dt seconds 4 dt hours

Warning

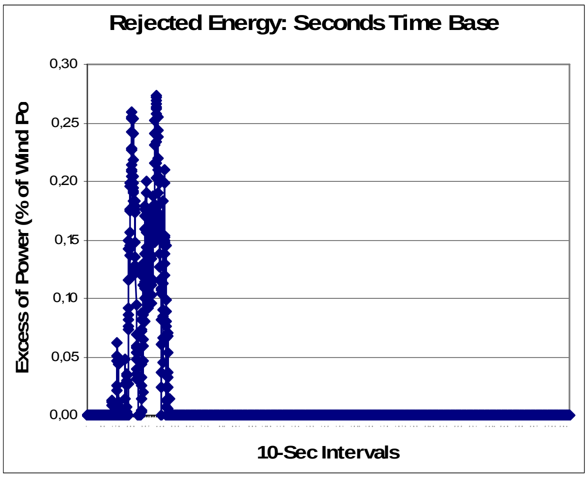
1 To compare partial loads at different time scale: choose one number of turbine and vary the Study Time Base 0 to 2 and then to 3
It is even more important to vary n Turbines 0 to 9 for "Savings Results (needs results winthout turbines before), advice:

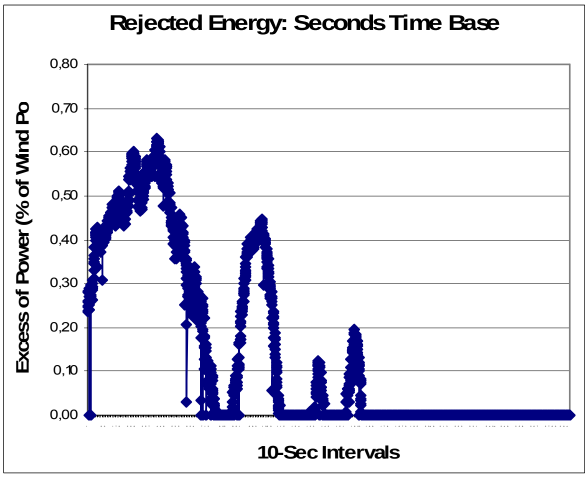
2 The curves for direct comparison of several curves not vs number of turbines on a same sheet, depend on the actual parameter in "Excess&WindP. They are intermediate results used then in the table for variable n of turbines. The reference "Active sheet" allows to define the concerned sheet as active or not, in order to block the results of this sheet and then to not influence the results anymore.

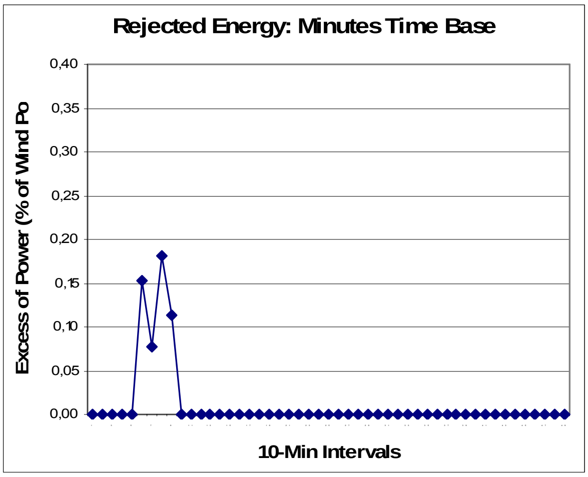
Appendix 6: Influence of the Time Scales on Wind Penetration and Rejected Energy Results at Different Number of Turbines (4 and 8 WT)

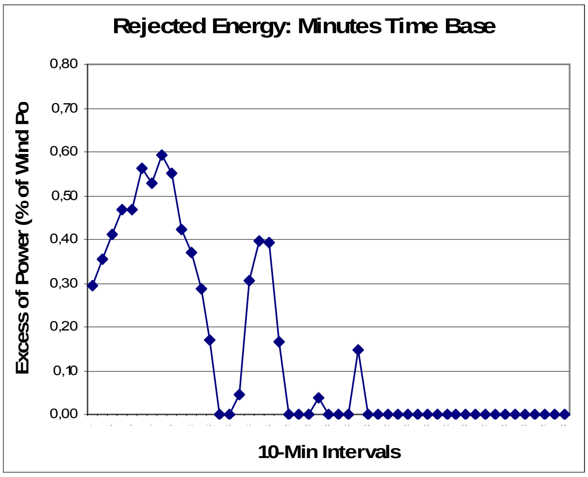
4 Wind Turbines

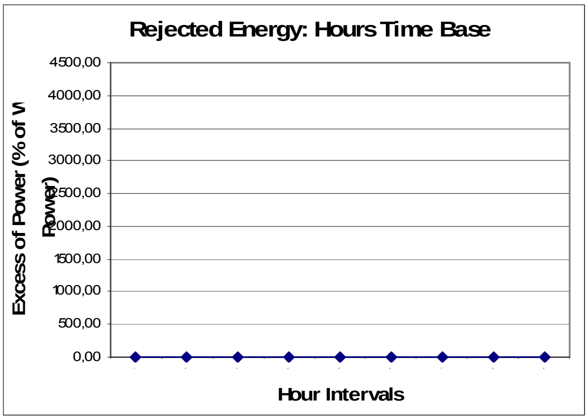
8 Wind Turbines

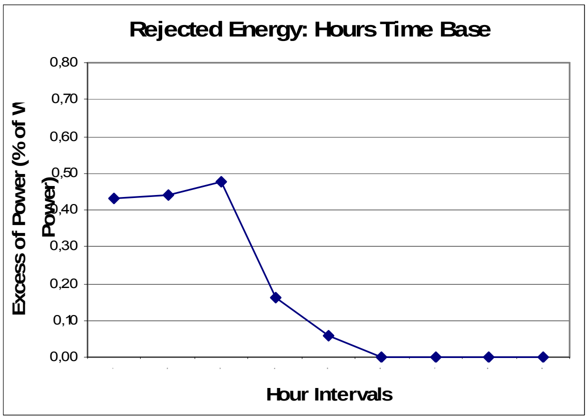












Appendix 7: Model's Calibration for the Diesel Reaction Analysis

In blue the active cell directly influenced by LLD strategies

number of values theoritic	8	number of used values **'+2 for min & sec '+1 for hours** due to non-use of the first values & **'+2 for sec** due to 2 missing values			
number of values used	7				
hours/ study period	8	197=(8*24+5) if Long Time period, 8 if Short Time Period	ratio	1,142857143	Aim: Adjust Stop&Run to theoritical 8 hours

DIESEL 1		DIESEL 2		DIESEL 3		DIESEL 4	
n time off / n values real	7,00	n time off / n values real	7,00	n time off / n values real	4,00	n time off / n values real	1,00
STOP hours/study period	8,00	STOP hours/study period	8,00	STOP hours/study period	4,57	STOP hours/study period	1,14
STOP%	100,00%	STOP%	100,00%	STOP%	57,14%	STOP%	14,29%
RUN hours/study period	0,00	RUN hours/study period	0,00	RUN hours/study period	3,43	RUN hours/study period	6,86
RUN%	0,00%	RUN%	0,00%	RUN%	42,86%	RUN%	85,71%
Total kW produced	0,00	Total kW produced	0,00	Total kW produced	2400	Total kW produced / n values used	5234
Average kW produced	0,00	Average kW produced	0,00	Average kW produced	342,82	Average kW produced/study period	747,73
n On	0	n On	0	n On	2	n On	1
n Fast On	0	n Fast On	0	n Fast On	1	n Fast On	0
		n Off	0			n Fast Off	0
		n Fast Off	0			number of problem on Pnom	0
						number of problem on Diesel 4	0

Appendix 8: Saved and Extra Production for the Set-Up and for the Respective Diesel Engines over the Short Time Period

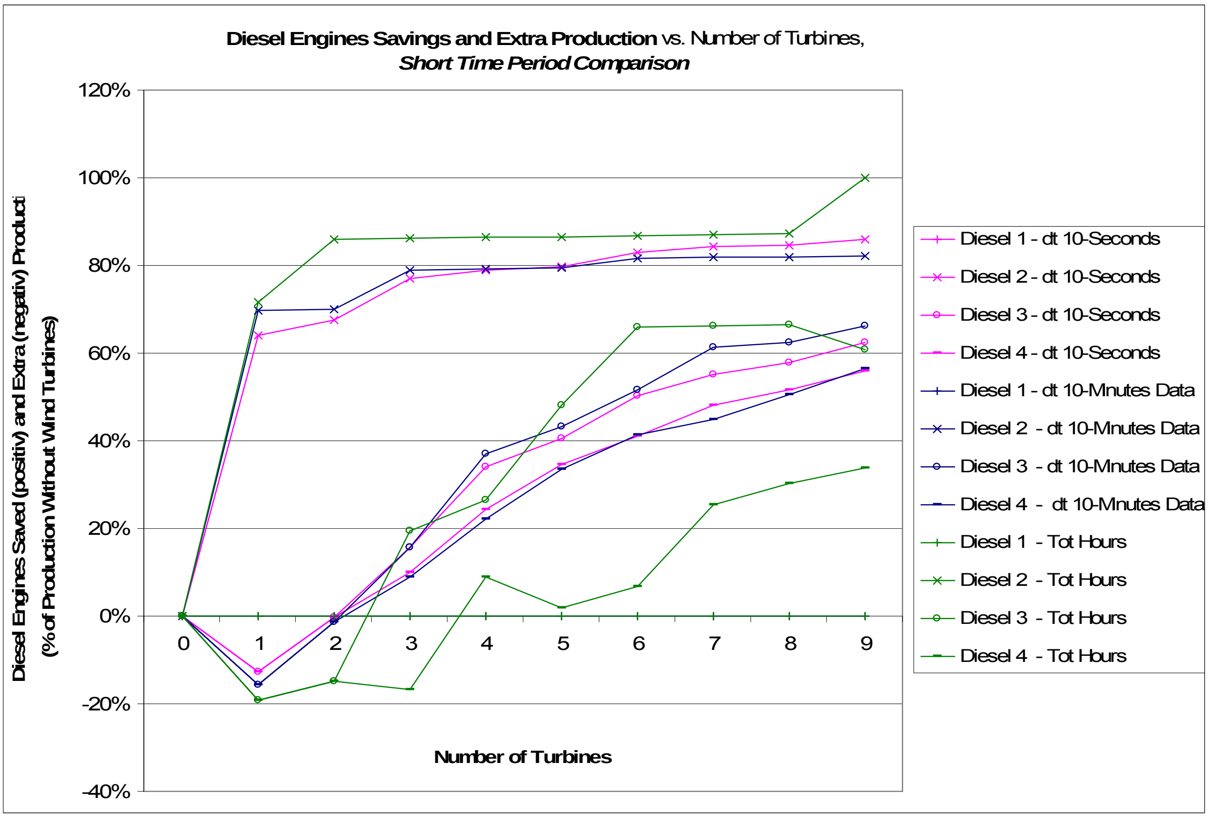


Figure: Diesel Engines Saved and Extra Productions vs. Number of Turbines, Times Scales Comparison over the Short Time Period

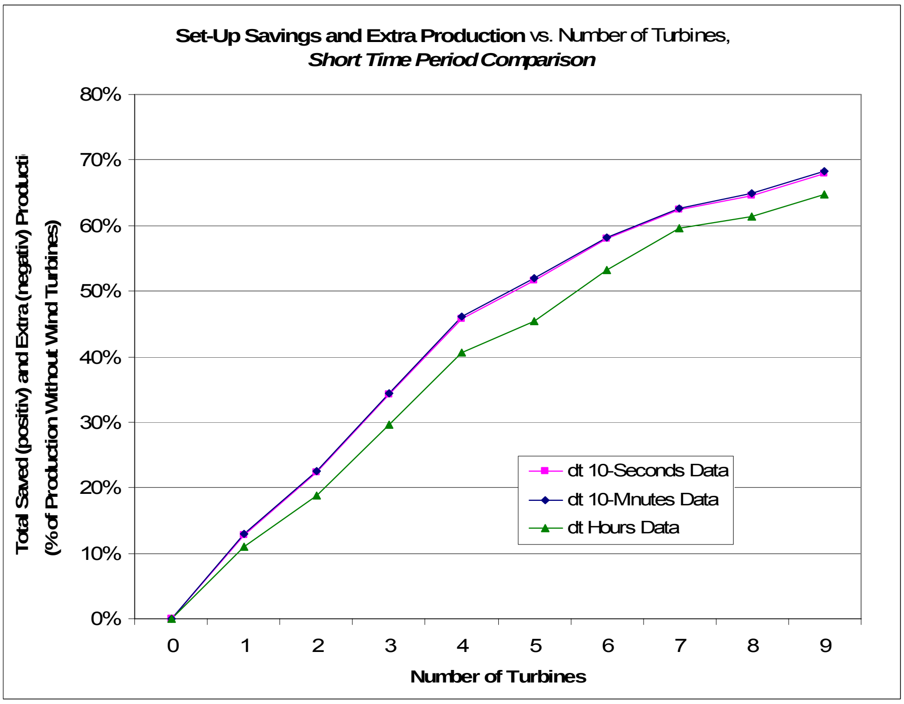


Figure: Diesel Set-Up Saved and Extra Productions vs. Number of Turbines, Times Scales Comparison over the Short Time Period

Appendix 9: Rejected Energy vs. Number of Turbines Considering LLD Strategies, Time Scales Comparison over the Long and Short Time Periods

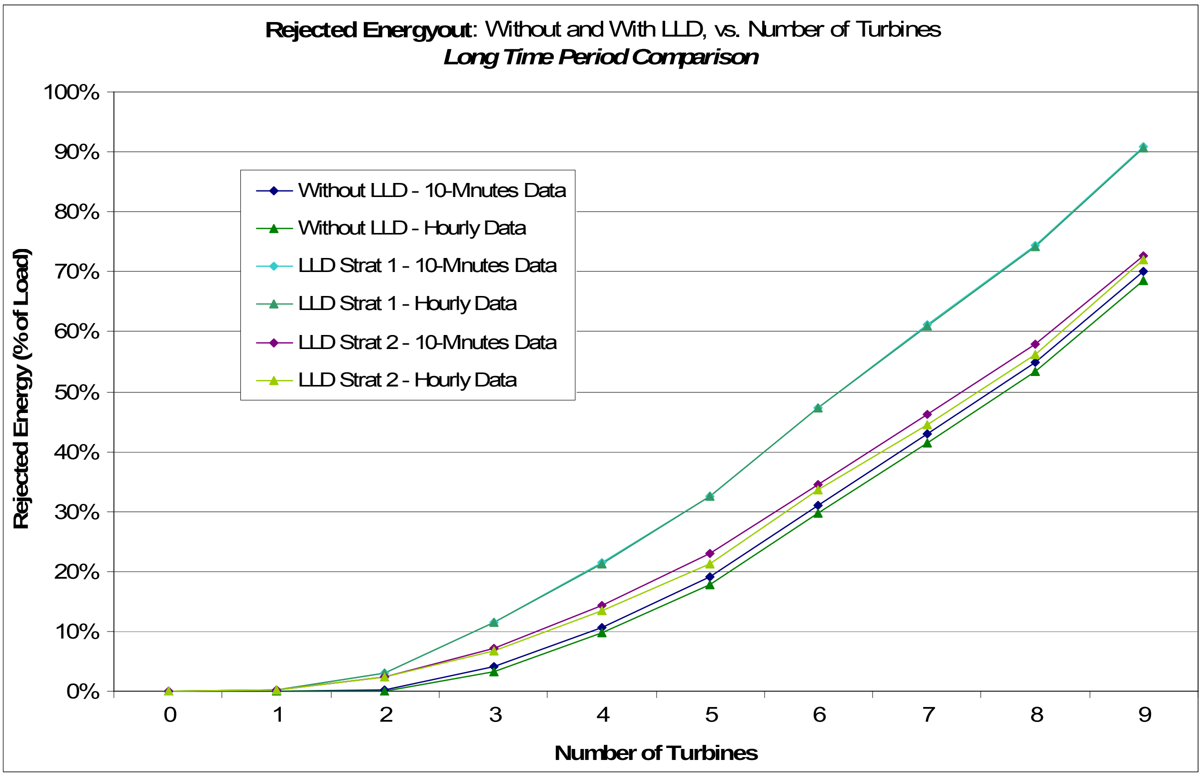


Figure: Rejected Energy Considering LLD Strategies vs. Number of Turbines, Time Scales Comparison over the Long Time Period

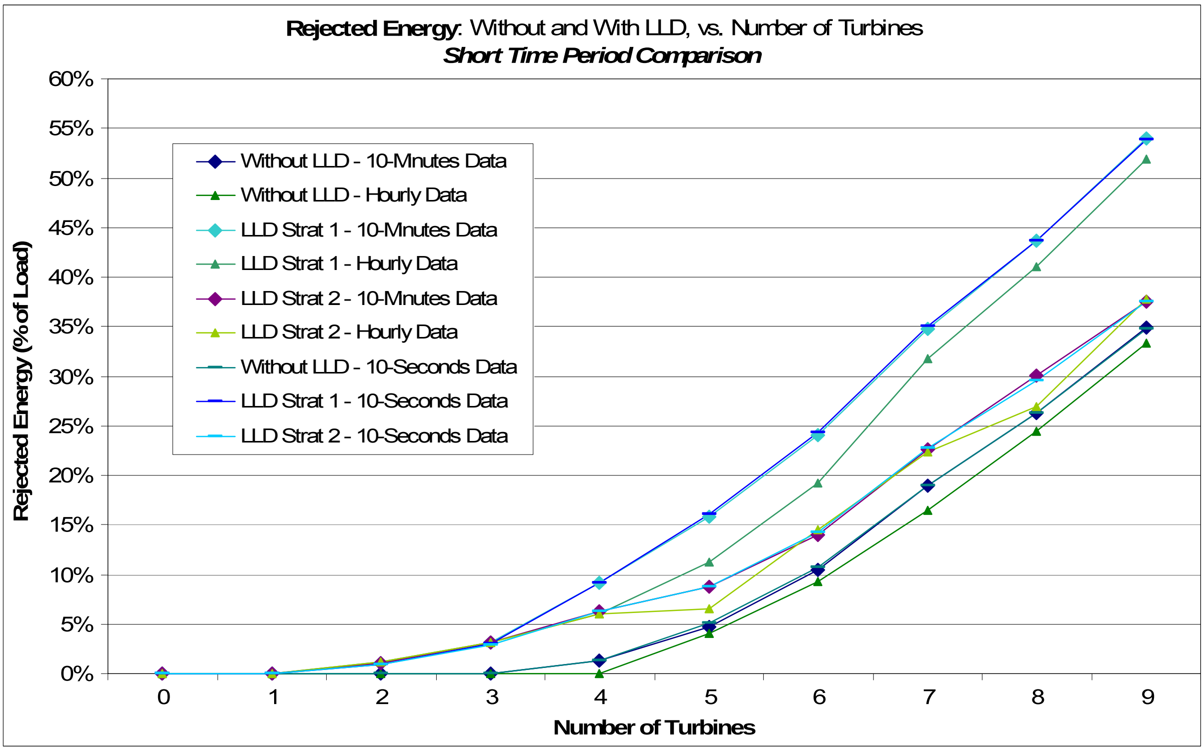


Figure: Rejected Energy Considering LLD Strategies vs. Number of Turbines, Time Scales Comparison over the Short Time Period

Appendix 10: Resulting Curves of the Diesel Engine Size Effect Analysis, achieved with three Level of Nominal Power (500; 1,200 and 2,000 kW)

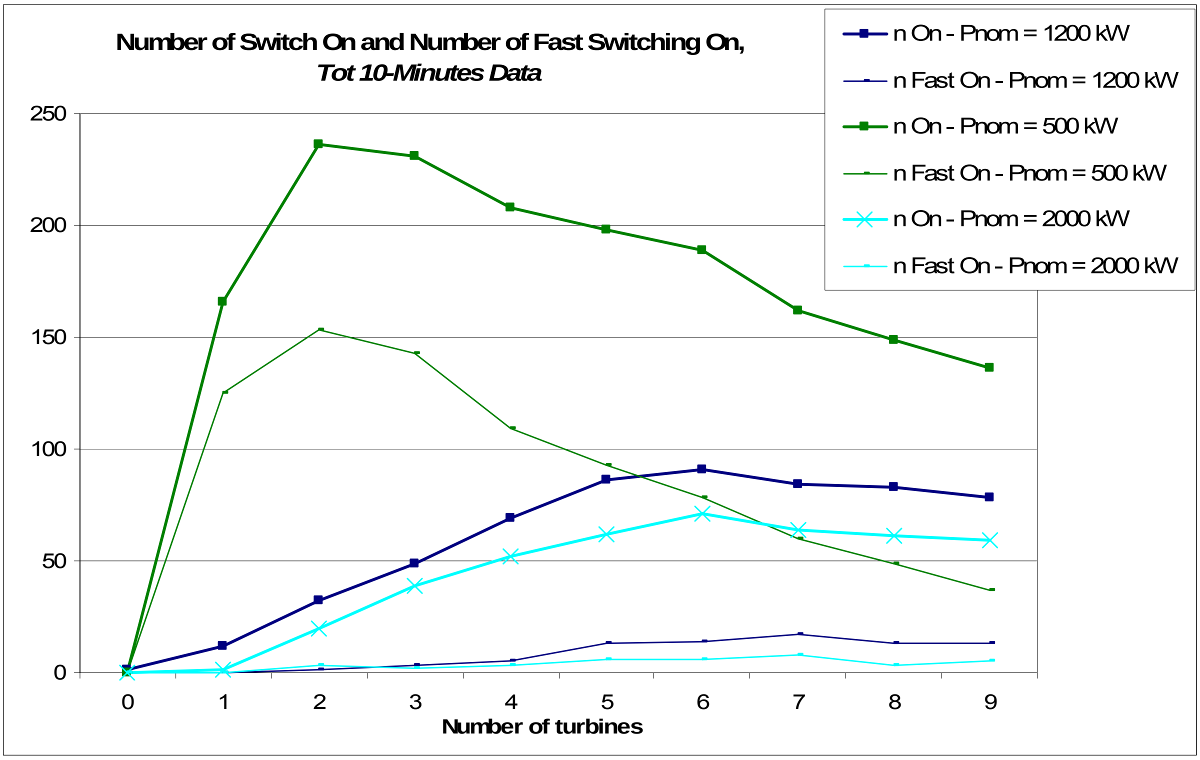


Figure: Number of Switching On and Fast Switching On for the whole Diesel Set-Up, 10-Minutes Data over the Long Time Period

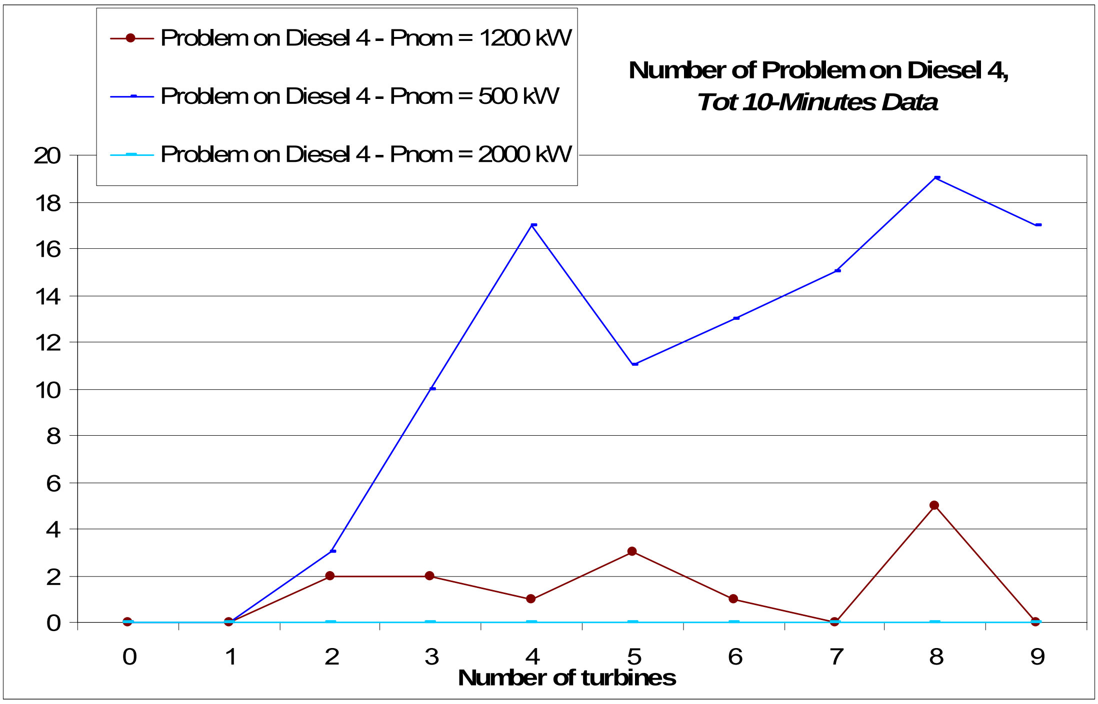


Figure: Number of Switching On of the Fourth Engine, 10-Minutes Data over the Long Time Period

Appendix 11: Resulting Curves of the Variable Load Effect Analysis

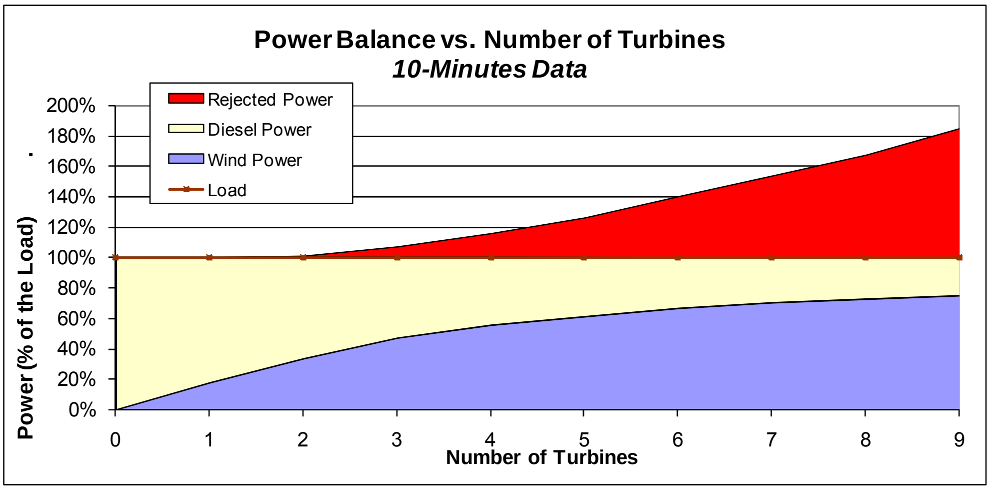


Figure: Power Flows in Percentage of the Load vs. Number of Turbines, 10-Minutes Data over the Long Time Period

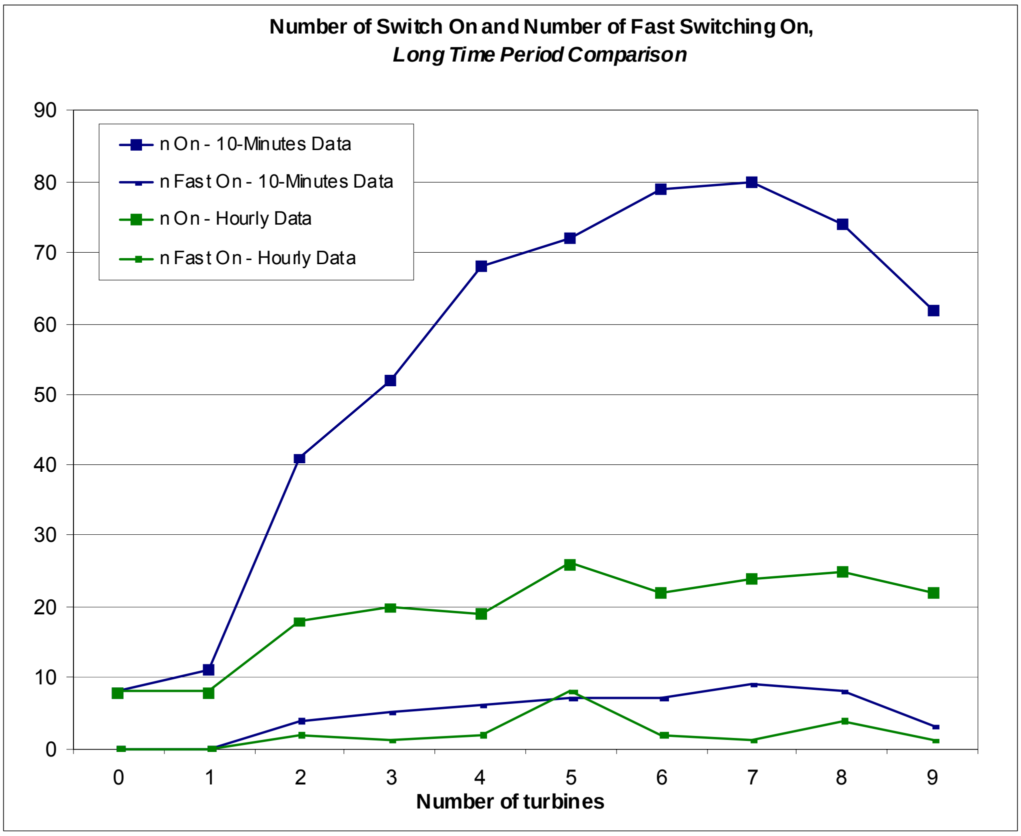


Figure: Number of Switching On and Fast Switching On vs. Number of Turbines, Times Scales Comparison over the Long Time Period

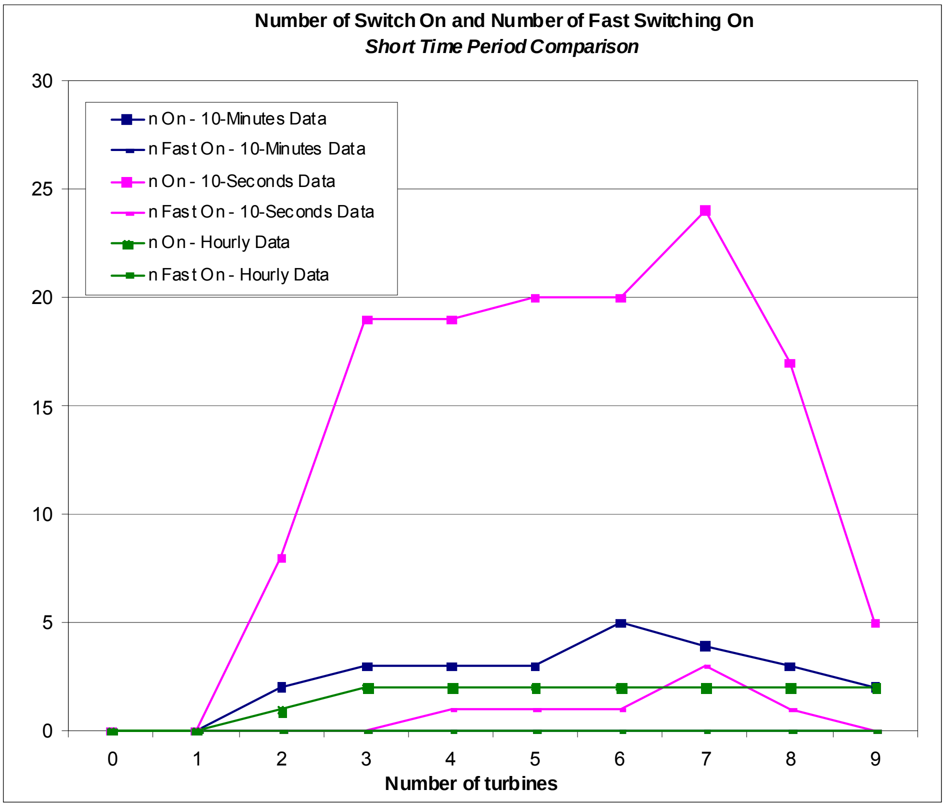


Figure: Number of Switching On and Fast Switching On vs. Number of Turbines, Times Scales Comparison over the Short Time Period

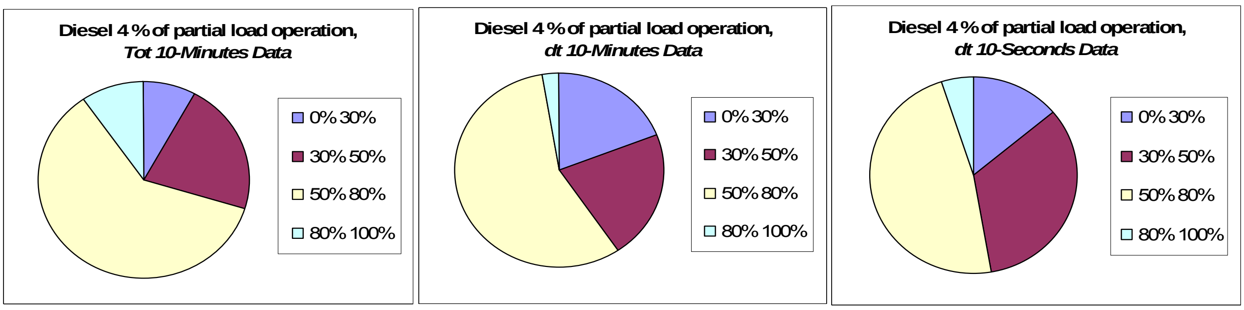


Figure: Fourth Diesel Engine Partial Load Distributions with 3 WT, Time Scales Comparison over the Short and Long Time Periods

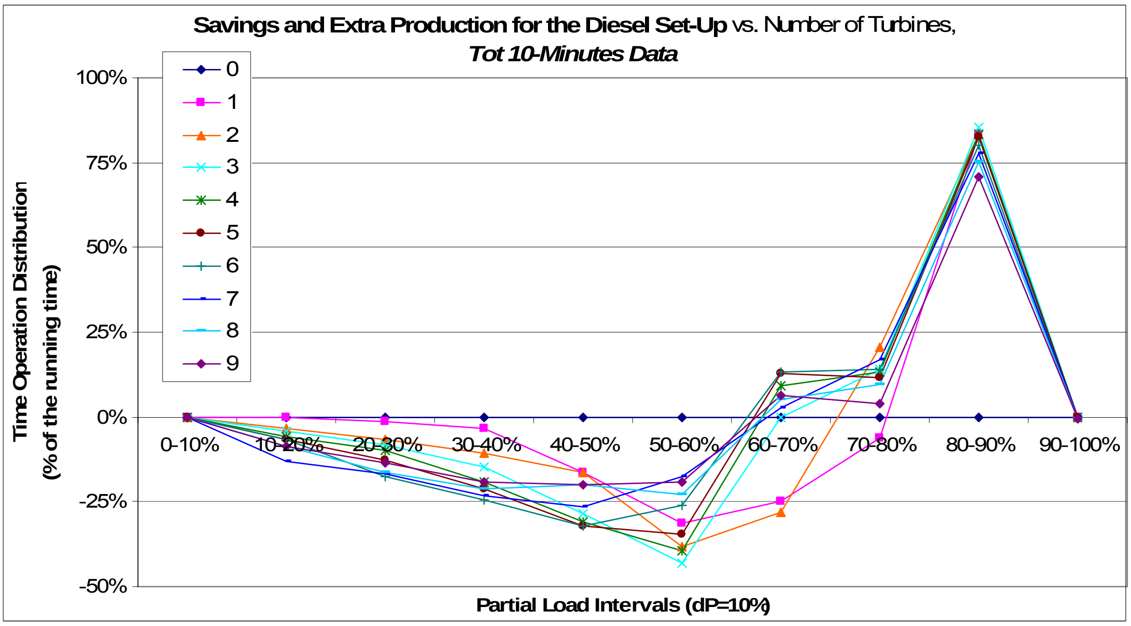


Figure: Saved and Extra Productions Regarding Diesel Engines Partial Loads Operation for 0 to 9 WT, 10-Minutes Data over the Long Time Period

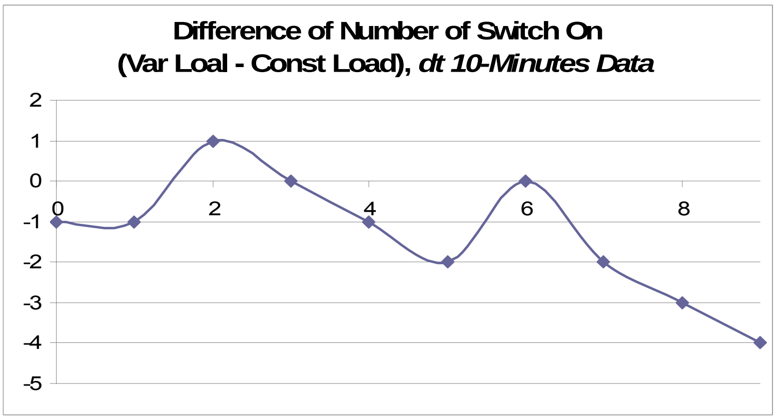


Figure: Number of Switching On, Difference between Constant and Variable Load Cases vs. Number of Turbines, 10-Minutes Data over the Short Time Period