



Overview of Supervisory Control Strategies Including a MATLAB[®] Simulink[®] Simulation Tool

PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T11-08:2012

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

**Overview of Supervisory Control Strategies
including a MATLAB® Simulink® Simulation Tool**

Report IEA-PVPS T11-08:2012

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1. Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) which carries out a comprehensive program of energy co-operation among its member countries. The European Commission also participates in the work of the IEA.

The IEA Photovoltaic Power Systems Program (PVPS) is one of the collaborative R&D Agreements established within the IEA. Since 1993, the PVPS participants have been conducting a variety of joint projects in the application of photovoltaic conversion of solar energy into electricity. The mission of the IEA PVPS program is: To enhance the international collaboration efforts which accelerate the development and deployment of photovoltaic solar energy as a significant and sustainable renewable energy option.

1. To stimulate activities that will lead to a cost reduction of PV power systems applications.
2. To increase the awareness of PV power systems' potential and value and thereby provide advice to decision makers from government, utilities and international organizations.
3. To foster the removal of technical and non-technical barriers of PV power systems for the emerging applications in OECD countries.
4. To enhance co-operation with non-OECD countries and address both technical and non-technical issues of PV applications in those countries.

The overall program is headed by an Executive Committee composed of one representative from each participating country, while the management of individual research projects (Tasks) is the responsibility of Operating Agents. By mid 2010, thirteen Tasks were established within the PVPS program.

The overall goal of Task 11: "PV Hybrid Systems within Mini-grids" is to promote the role of PV technology as a technically relevant and competitive source in mini-grids. It aims at enhancing the knowledge-base of multi-source power generation systems including PV and associated electric distribution networks. The objectives of the Task are to:

- provide recommendations on individual designs (mix of technologies, architecture, size, performances, other) in order to achieve high penetration level of PV as a mean to improve quality, reliability and economics of electrification systems such as mini-grids;
- assess the potential of technologies to be mixed with PV for hybridisation.

The current members of the IEA PVPS Task 11 are:

- Australia
- Austria
- Canada
- China
- France
- Germany
- Italy
- Japan
- Malaysia
- Spain
- United States of America

This report describes supervisory control strategies for PV hybrid systems, presents a computer simulation model for evaluating the performance of these strategies, and demonstrates the use of the simulation model with a case study. The technical report has been prepared under the supervision of PVPS Task 11 by: M. Vandenberg, C. Garza, and A. Notholt-Vergara of the Fraunhofer Institute for Wind Energy and Energy Systems Technology, Kassel, Germany

The report expresses, as nearly as possible, the international consensus of opinion of the Task 11 experts on the subject dealt with. Further information on the activities and results of the Task can be found at: <http://www.iea-pvps-task11.org> and <http://www.iea-pvps.org>.

2. Executive Summary

Designing the supervisory control is one of the most critical tasks in the planning process for hybrid systems and mini-grids. Even if the system is correctly sized and able to accommodate unforeseen events, a badly-planned supervisory control may lead to sub-optimal performances, longer downtimes and premature failure of the system.

Within the frame of IEA PVPS Task 11 “PV Hybrid Systems within Mini-grids”, the state of the art in the field of dispatch strategies for generation sources and loads has been investigated. The following different possible goals of the supervisory control have been identified:

- Best economical operation
- Highest reliability
- Lowest carbon footprint
- Service delivery optimization
- Component lifecycle optimization
- Load optimization through demand side management
- Best quality of supply

Based on available dispatch control parameters, several supervisory control strategies are presented for typical hybrid system design categories. The designs are categorized according to the solar fraction, the level of load dispatchability, and the availability of storage. For each design category, one or several adapted dispatch strategies are identified. In total, ten dispatch strategies are described.

In reality, many hybrid systems cannot be classified easily and different control strategies should be compared. In view of the many different system design configurations, weather conditions and load profiles, it is important to simulate in detail the impact of the supervisory control strategy on the overall performance. As a result of the work on this activity, simulation software using the MATLAB[®] system was developed at the Fraunhofer Institute for Wind Energy and Energy Systems Technology, Kassel, Germany. This tool may be used as an aid for anticipating possible critical system states and to evaluate the performance of a given supervisory control strategy. Standard power units with their control parameters are provided. The simulation software model (tested with Simulink[®] 7.0) may be downloaded from the Task 11 web-site (www.iea-pvps-task11.org).

In the last Section of the report, the simulation tool is applied on a virtual mini-grid. Two different supervisory strategies are compared in terms of their technical and economic impacts. The simulation results confirm that a significant amount of fuel savings can be achieved by choosing an appropriate dispatch strategy.

3. Introduction

Designing the supervisory control is one of the most critical tasks in the planning process for hybrid systems and mini-grids. Even if the system is correctly sized and able to accommodate unforeseen events, a badly-planned supervisory control may lead to sub-optimal performances, longer downtimes and premature failure of the system.

Activity 23 of IEA PVPS Task 11 has the objective to describe supervisory control strategies for the dispatch of generation sources and loads, and to provide a tool for evaluating their performance under various scenarios. The specific objectives of this activity are:

- To integrate the state of the art of high-level grid control in utility systems into a set of parameters that are suitable for supervisory control of mini-grids,
- To define these control parameters, such as energy dispatch, load requirements, mix of generation sources, optimized use of renewables, maximization of economic return, controlled number of starts of diesel generators, central vs. distributed control, load shedding (active load control), information on available PV power, remote monitoring of systems and reporting and maintenance,
- To base a control strategy on the parameters determined as above,
- To apply the defined strategy to a case study.

As a result of the work on this activity, simulation software using the MATLAB[®] system was developed by Dr. Vandenberg at the Fraunhofer Institute for Wind Energy and Energy Systems Technology, Kassel, Germany. This tool may be used as an aid for anticipating possible critical system states and to evaluate the performance of a given supervisory control strategy. The simulation software model (tested with Simulink[®] 7.0) may be downloaded from the Task 11 web-site (www.iea-pvps-task11.org).

In Section 4, the state of the art about supervisory control is presented.

In Section 5, the simulation software modules are described.

Finally, the case study results are presented in Section 6.

4. The Supervisory Control

4.1 System Definition of the Supervisory Control System

The supervisory control system is the overlaying control of a mini-grid, which organizes and schedules the medium and long term energy flow in the power system, and aims to achieve an optimal operation of the system as a whole.

The supervisory control system manages the dispatching and control of all the active components of a mini or a micro grid. As seen in Figure 1, a mini-grid may be composed of a set of components such as:

- loads
- deferrable
- non-deferrable
- dispatchable generators
- storage devices
- renewable energy generators
- optionally, a connection to a larger grid

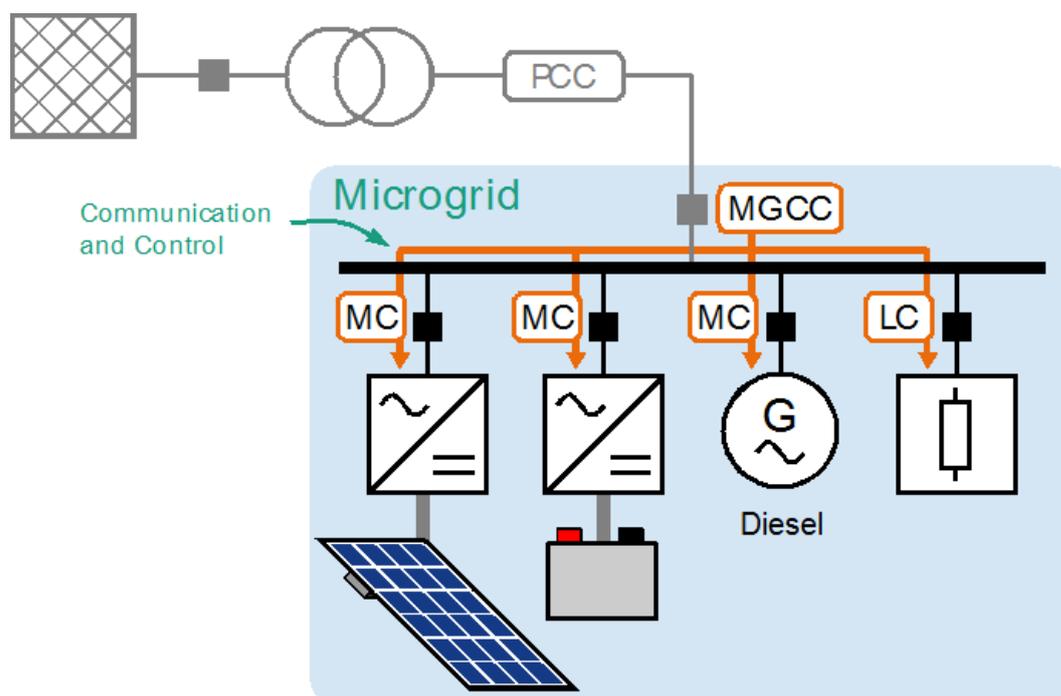


Figure 1 – Main components of a micro grid.
 The supervisory control (or the Micro Grid Control Center) manages the dispatch of the different micro generators through their respective Microgeneration Controllers and controls the dispatchable loads through the Load Controller.

The supervisory control may be regarded as a piece of intelligence (an embedded software, a computer algorithm or such) which aims to achieve optimal system operations. “Optimal system operation”, however, depends on a set of goals, rules and constraints, which are to be defined before the system is to be developed. The following Sections provide an overview of the most common goals, rules and constraints used in mini-grids.

4.2 Supervisory Control Goals

Goals definition strongly depends on the application context, load profiles, available generation and customers (loads). Some of the aims usually considered are described below.

4.2.1 Best Economical Operation (Least O&M Costs)

This strategy aims to minimise operation and maintenance (O&M) costs. The gensets will generally operate at best efficiency levels, and energy dumping will be avoided. This strategy may not achieve full use of the input from the solar generator, or minimise the system’s greenhouse emissions.

4.2.2 Highest Reliability

This strategy prioritizes system reliability. This will generally involve the maintenance of backup contingency gensets in a multi-genset system, and a greater amount of scheduled maintenance. This may impact service delivery.

4.2.3 Lowest Carbon Footprint (or Highest Renewable Energy Fraction)

This strategy optimizes the use of the renewable generator input, to minimize diesel genset operation. In some cases, this can lead to increased start-stop-cycles of the gensets.

4.2.4 Service Delivery Optimization

This strategy prioritizes service delivery, and is likely to imply a greater amount of generator runtime. In a multigenerator system, a larger amount of spinning reserve may be maintained. This schedule implies greater O&M costs and reduced system lifetimes.

4.2.5 Component Lifecycle Optimization

This strategy will configure the system to maximize component lifetime, particularly batteries. Component sizing and generator control will optimize battery cycling for efficient lifecycle operation. This strategy may include service delivery restrictions.

4.2.6 Load Optimization Through Demand Side Management

This strategy aims to optimize system operation through controlling the load via demand side management. By deferring loads to periods of solar input where

possible, the energy storage demands can be minimized, and generators are able to operate at better efficiencies.

4.2.7 Best Quality of Supply

In this case, electricity quality variables such as voltage range, harmonic distortion, etc. are prioritized. This may require the use of generators as spinning reserve and/or compensation nodes. This will result in lower system efficiencies, and increase costs.

In reality, operation control strategies generally incorporate multiple objectives in their design.

Figure 2 shows the goal distribution for two hybrid systems designed for different contexts.

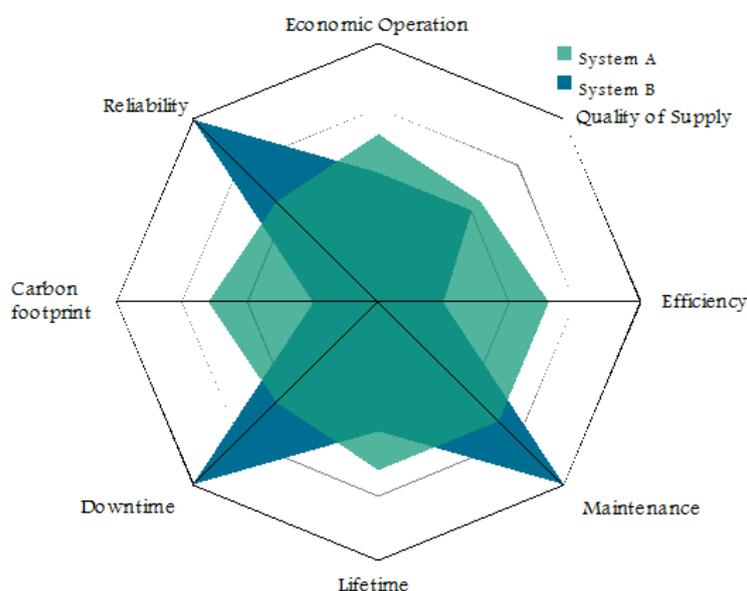


Figure 2 – Comparison of different goals for a supervisory control (System A: Generic NGO-financed rural electrification project, System B: System optimized for reliability)

- System A is a typical NGO-financed rural electrification project. In this case, there is a quite even distribution of the goals, with some more importance given to the economical operation, the carbon footprint, the lifetime and the reduced maintenance requirements.
- System B is a system optimized for reliability, for a remote application. This system sacrifices efficiency, carbon footprint and economic operation for higher reliability, lower downtime and lower maintenance.

4.3 Control Parameters

Figure 3 presents the components of a mini-grid with their control possibilities. Next to the technology, the typical degrees of freedom or “controllable characteristics” are listed. The means of control of each component category and their typical performance indicators are also listed. For components connected to the mini-grid, either directly or via a power conditioner (inverter), energy dispatch control signaling can be achieved via mains communications protocol, using minimal additional communications equipment.

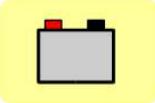
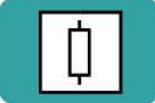
Technology	Controllable Characteristics	Control Possibilities	Performance
	<ul style="list-style-type: none"> Power throttling 	<ul style="list-style-type: none"> Communication line Frequency ☒ 	<ul style="list-style-type: none"> PR, PF Yield
	<ul style="list-style-type: none"> Depth of discharge Number of cycles per day Charge/discharge power 	<ul style="list-style-type: none"> Communication line Frequency ☒ Energy Management 	<ul style="list-style-type: none"> PR Efficiency
	<ul style="list-style-type: none"> Number of start/stop cycles Generation power 	<ul style="list-style-type: none"> Communication line Start/Stop signal Frequency 	<ul style="list-style-type: none"> Number of starts Fuel yield [kWh/L] Operating hours
	<ul style="list-style-type: none"> Power consumption (on/off) 	<ul style="list-style-type: none"> Communication line Frequency User 	<ul style="list-style-type: none"> Availability Consumption

Figure 3 – Controllable characteristics and means of control for components typically found on mini-grids. The ☒ symbol represents features that require an AC-coupling device such as an inverter.

4.4 Supervisory Control Strategies for Typical Hybrid System Design Categories

Depending on hybrid system design, classical control strategies can be identified. In the proposed approach, the hybrid system designs are classified according to high or low values for the solar fraction level, the dispatch capability of loads and the size of the electrical storage. Real systems might not fit completely in one of these categories and simulations would then be needed for choosing the best control strategy. Additional strategies can be found in [1].

Five different system configuration categories have been identified, describing major hybrid system architectures. Several different control strategy options correspond to each system configuration category. Some of these strategies can further be combined.

Figure 4 and Figure 5 show the system configuration categories available. Figure 4 shows the categories that have small or no storage. Figure 5 shows configurations incorporating a significant storage component.

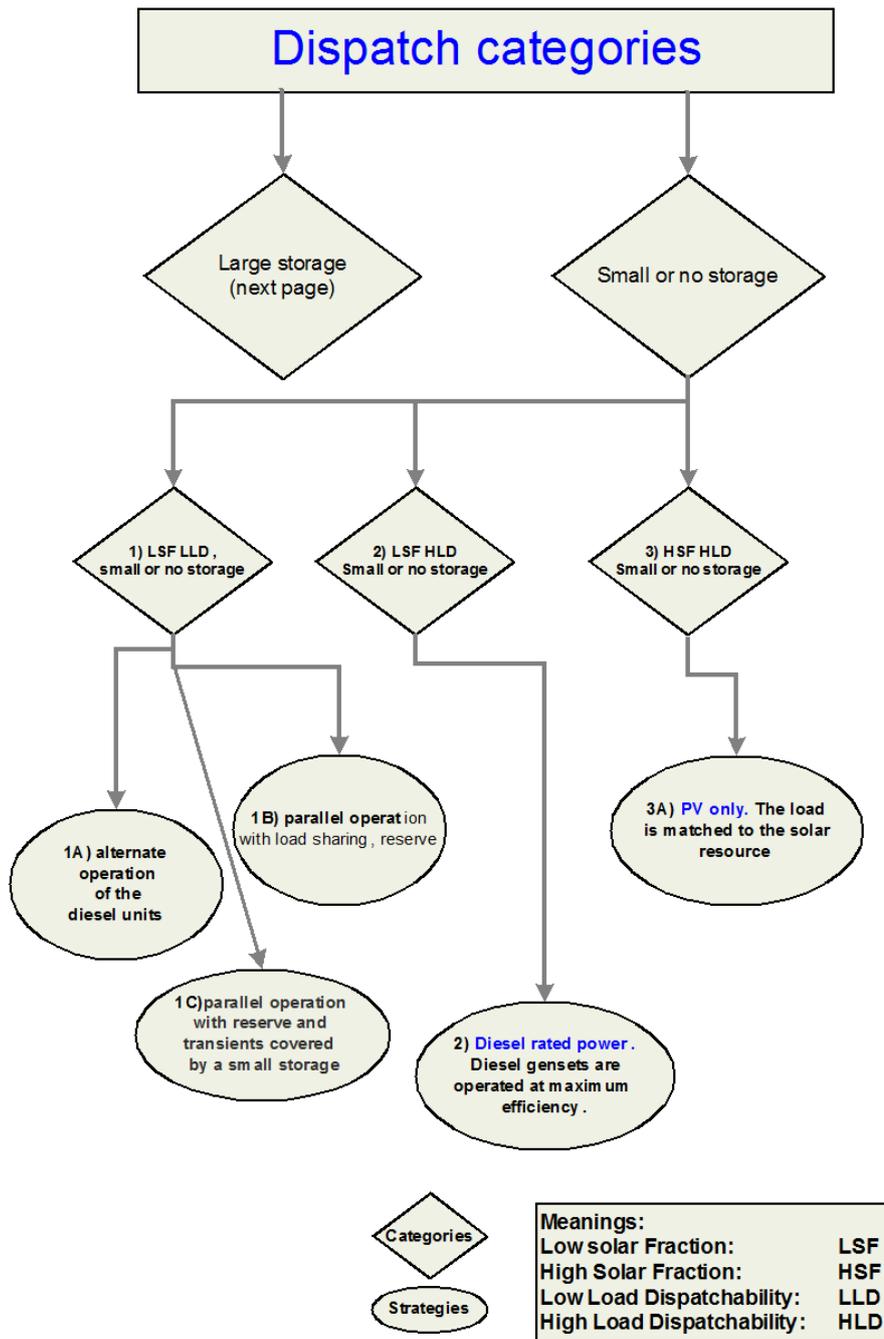


Figure 4 – Dispatch categories for systems with limited storage

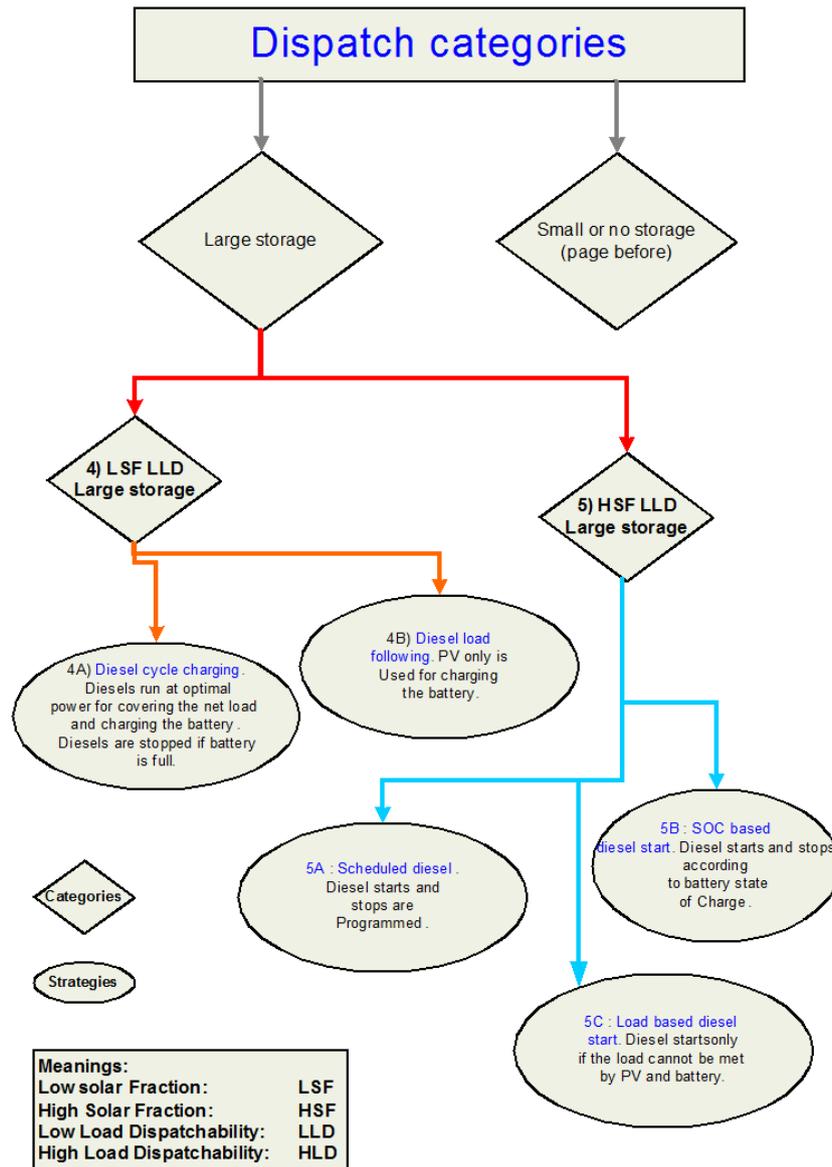


Figure 5 – Dispatch categories for systems with storage

4.4.1 Category 1

Low solar fraction, low load dispatch capability, small (or no) storage

- **Strategy 1A - Alternate operation of the diesel units.**

In this strategy only one diesel genset is used at any time. Parallel operation of gensets is never used. A new genset is put in operation every 24 hours. Typically, this situation corresponds to a power plant with identical gensets having a rated power bigger than the peak load. During low demand periods or when the solar panels are providing energy, the genset will operate inefficiently at a very low loading. In this strategy the only optimization of the operation would be to agree, if possible, on switching off the power plant during period of time (e.g. by night after 23:00).

- **Strategy 1B - Parallel genset operation, with load sharing, reserve and transients covered by diesel.**

Under this strategy the diesel gensets are able to operate in parallel, sharing the required power production. The synchronization and parallel operation can be organized automatically or manually. No storage is available and gensets are providing the necessary reserve power. The optimization parameters correspond to planning the starting and stopping of the different gensets in order to minimize the fuel consumption while keeping a secure and reliable system. Tools for load and solar predictions could be used.

- **Strategy 1C - Parallel genset operation with reserve and transients covered by a small storage component.**

Compared to Strategy 1B, the reserve power is provided by a storage unit, capable of delivering very quickly a high level of power. The storage is able to provide the bridging energy needed for the cold starting and the synchronization of an additional genset. The same storage is also used for smoothing the fluctuations of the load and of the renewable sources.

4.4.2 Category 2

Low solar fraction, high load dispatch capability, small (or no) storage

In this type of design, the security level is very high and the load can be dispatched in order to operate the diesel gensets at their maximum efficiency.

4.4.3 Category 3

High solar fraction, high load dispatch capability, small (or no) storage

This category corresponds to a photovoltaic only system that operates only when there is sufficient solar input, e.g. a water pumping system with a reservoir. The load profile is matched to the solar production curve.

4.4.4 Category 4

Low solar fraction, low load dispatch capability, high storage capacity

- **Strategy 4A - PV and diesel genset-based battery charging.**

The gensets are operated at their optimal efficiency level to cover the load and charging the battery with the surplus power. Typically, the diesel gensets are running when the load level is high in order to reduce the amount of energy to be stored in the battery. When the load level is low, the load can be directly fed by the battery and the gensets can be switched off in order to avoid inefficient low loading operation.

- **Strategy 4B - PV battery charging only.**

In this scenario, batteries are charged by PV only. The gensets are not able to charge the batteries. The main role of the battery is to shift solar power use to optimal periods of the day.

4.4.5 Category 5

High solar fraction, low load dispatch capability, high storage capacity

- **Strategy 5A - Scheduled genset.**

The Diesel genset operates according to a predetermined scheduled program (e.g. 1 hour every evening). With such a strategy, it is difficult to optimize the battery charging and the operation of the genset, according to the fluctuations of the daily solar resource.

- **Strategy 5B - SOC-based diesel operation.**

Under this strategy, the diesel genset operates according to the battery state of charge (SOC). This strategy provides both reliability in meeting the load, and confidence that batteries are being cycled appropriately. The risk with this method would be a wrong SOC estimation by the control system.

- **Strategy 5C - Load-based diesel operation.**

In this strategy, the diesel genset operates when the load power exceeds the combined capacity of the storage and PV. This guarantees a correct loading for the genset.

Strategies 5A, 5B and 5C can be combined in order to get an efficient and robust operation.

5. Description of the Simulation Tool

5.1 Overview

Simulation tools can be used to model the performance outcomes of a control schedule. The tool investigated here was developed by Dr. Vandenberg at the Fraunhofer Institute for Wind Energy and Energy Systems (IWES) Technology, Kassel, Germany. The simulation software model (tested with Simulink[®] 7.0) may be downloaded from the Task 11 web-site (www.iea-pvps-task11.org).

The tool is designed to test supervisory control strategies over a long period of time (e.g. 1 year), for mini-grids with up to 10 different dispatchable power units (generator, storage and load components).

The code has been tested under Simulink 7.0, with a fixed size, discrete time step of 15 minutes. Other time steps could also be used. No specific Matlab[®]/Simulink toolboxes are required. The user defines the control strategy via C code (Matlab[®] Sfunction). Based on the monitoring results from the last time step, new active power setpoints are specified for the dispatchable power units. Each dispatchable unit has its own local controller which will accept or reject the required setpoint. Differences between total generation and load power can be balanced by the primary control mechanism, which will increase or decrease slightly the grid frequency and consequently modify the power output of some units via implemented droop functions. This balancing process implies the use, at each time step, of the Matlab algebraic loop solving function "fzero". The quality of the supervisory strategy is evaluated by the economical outputs like cost or fuel consumption.

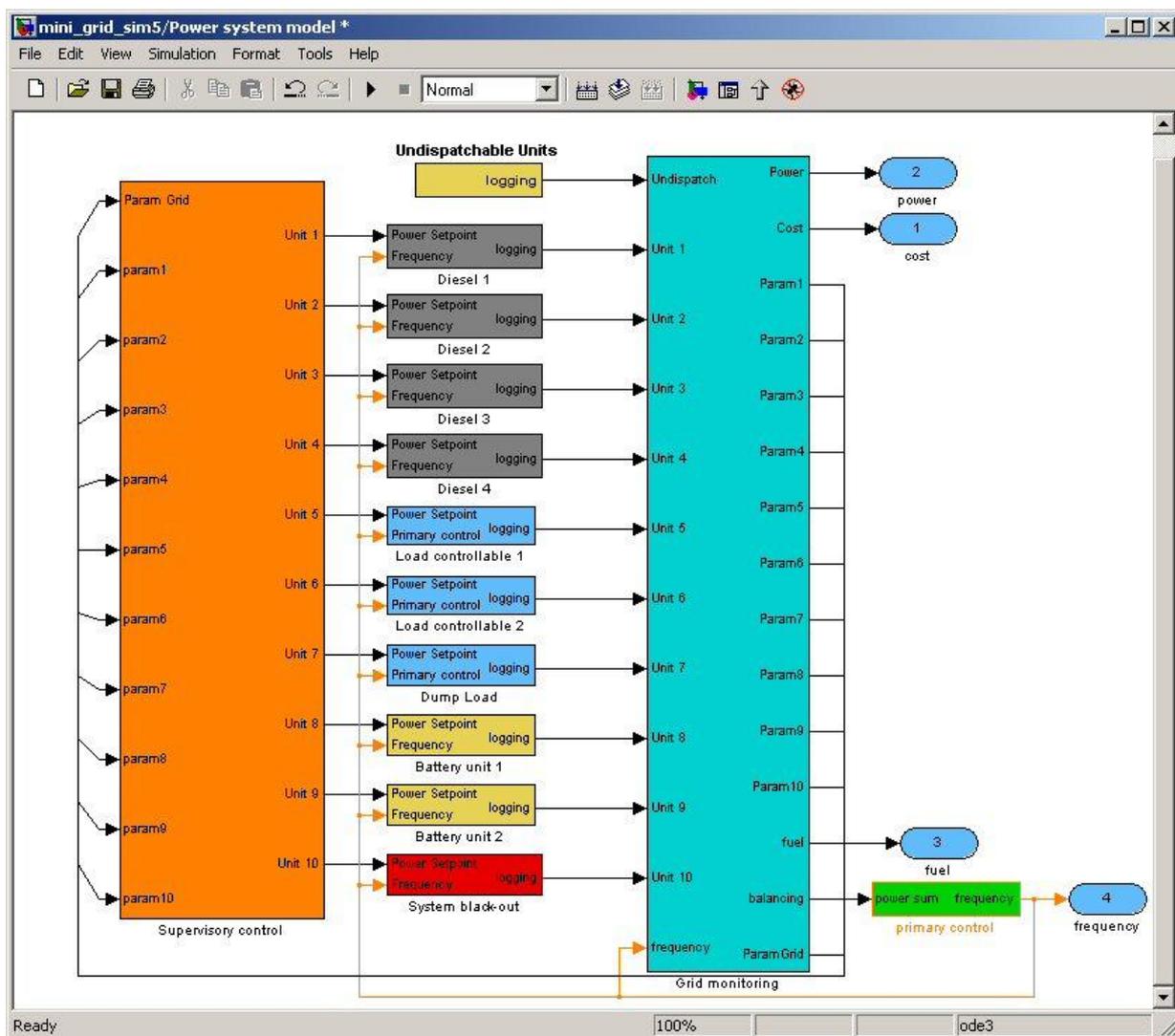


Figure 6 – Power system model

5.2 Power Unit Model

The Power Unit Model is a pre-assembled configuration that includes a diesel generator, battery storage, a deferrable load (typically a pumping unit combined with water storage) and a dump load. A typical unit model includes a local controller, a local monitoring system and a cost calculation module (Figure 7). In the local controller, the user specifies the generator constraints and droop functions. The cost module estimates the annual cost (investment + O&M + fuel). Component lifetimes are modeled.

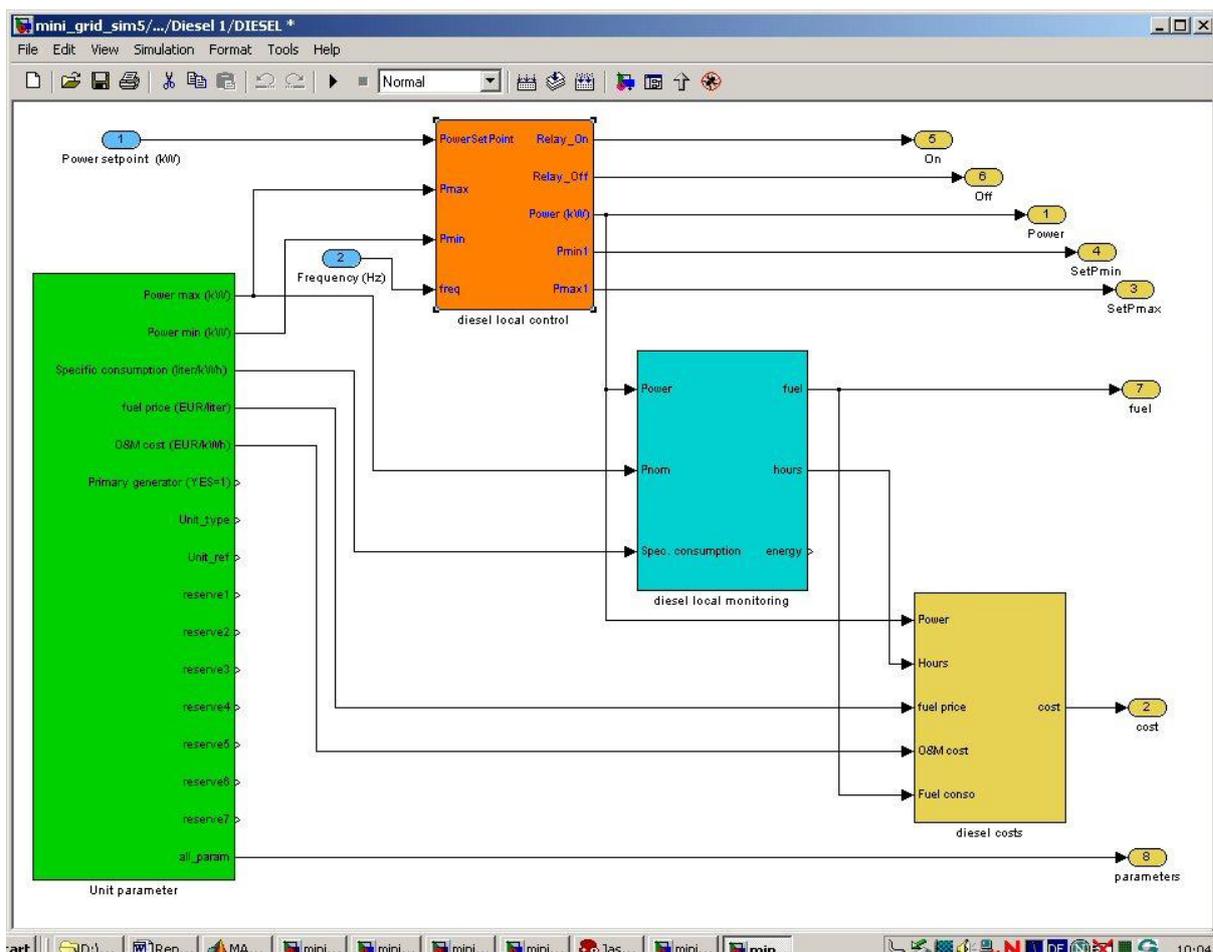


Figure 7 – Example of model for a dispatchable diesel generator unit.

5.3 Simulation Inputs

The user can specify the following inputs:

1. A maximum number of 10 dispatchable power units
2. For each dispatchable power unit: unit specifications, programmable local control parameters, and economic variables.
3. Programmable load profiles for non-dispatchable loads
4. Programmable power generation profiles for all non dispatchable generators (e.g. PV)
5. Simulation parameters (time step, duration)

5.4 Supervisory Control

Supervisory control strategies are specified by the user as a C code (Matlab® C Sfunction). Based on monitoring information from the last time step, the supervisory control generates setpoints for the active power of all 10 dispatchable units. Examples of C codes are provided with the files “power_dispatch_iea1.c”, “power_dispatch_iea2.c”, “power_dispatch_iea3.c”. Only “mdlOutputs” function in the supervisory code has to be modified for defining a new dispatch strategy (Figure 8).

```

193 static void mdlOutputs(SimStruct *S, int_T tid)
194 {
195
196     const real_T *param_grid = ssGetInputPortRealSignal(S,0);
197     const real_T *param_unit1 = ssGetInputPortRealSignal(S,1);
198     const real_T *param_unit2 = ssGetInputPortRealSignal(S,2);
199     const real_T *param_unit3 = ssGetInputPortRealSignal(S,3);
200     const real_T *param_unit4 = ssGetInputPortRealSignal(S,4);
201     const real_T *param_unit5 = ssGetInputPortRealSignal(S,5);
202     const real_T *param_unit6 = ssGetInputPortRealSignal(S,6);
203     const real_T *param_unit7 = ssGetInputPortRealSignal(S,7);
204     const real_T *param_unit8 = ssGetInputPortRealSignal(S,8);
205     const real_T *param_unit9 = ssGetInputPortRealSignal(S,9);
206     const real_T *param_unit10 = ssGetInputPortRealSignal(S,10);
207     real_T *powerSetPoint = ssGetOutputPortRealSignal(S,0);
208     const int_T width = ssGetInputPortWidth(S,0);
209
210
211     //////////////////////////////////////
212     ////////////////////////////////////// strategy 1: all units on, no frequency control, batteries controlled at DOD 25%
213     //////////////////////////////////////
214
215     powerSetPoint[0]= 1; //diesel unit1 is used as balancing unit
216     powerSetPoint[1]= 1; //diesel unit1 is used as balancing unit
217     powerSetPoint[2]= 1; //diesel unit1 is used as balancing unit
218     powerSetPoint[3]= 1; //diesel unit1 is used as balancing unit
219     powerSetPoint[6]= -1; //Dump unit1 is used as balancing unit
220
221     // management of battery unit1
222     //Battery unit1 is used as balancing unit at DOD=25
223     if (param_unit8[6]<25)
224     {powerSetPoint[7]= 50; }
225     else
226     {powerSetPoint[7]= -50; }
227

```

Figure 8 – “mdlOutputs” function in the supervisory code describes the dispatch strategy.

5.5 Power Balancing

The supervisory control provides setpoints for the power output of the different generators. The supervisory control uses past monitoring data and most of the time, there will be a difference between total generated and consumed power. Primary control based on frequency droops implemented in generators is used to balance the deficit or excess of power generation. At each time step, the Matlab® algebraic loop solving function “fzero” is used to increase or reduce slightly the frequency from the nominal value, until the sum of generated power equals the load.

If the supervisory control were able to predict the load exactly, and to dispatch it between generators, no frequency deviations would occur.

5.6 Simulation Results

Simulation results are provided in 2 ASCII (csv) files. "results.csv" records the time series for power and total costs. "resultsTotal.csv" records statistics for the whole simulation period for energy and levelized cost.

6. Case Study - “Greek Island”

In this study, two supervisory strategies are tested on a virtual multi-diesel mini-grid system. According to the classification defined in Section 4.4, the strategies are similar to 1A and 1C.

6.1 Load Profile

The data provided by IWES with the simulation platform can be used to simulate a typical Greek island. The load profile normalized to 1kW peak is presented below. The load is characterized by a significant variation between winter and summer time, and by a significant evening peak. In the simulation, the load was scaled up to a 4 MW peak.

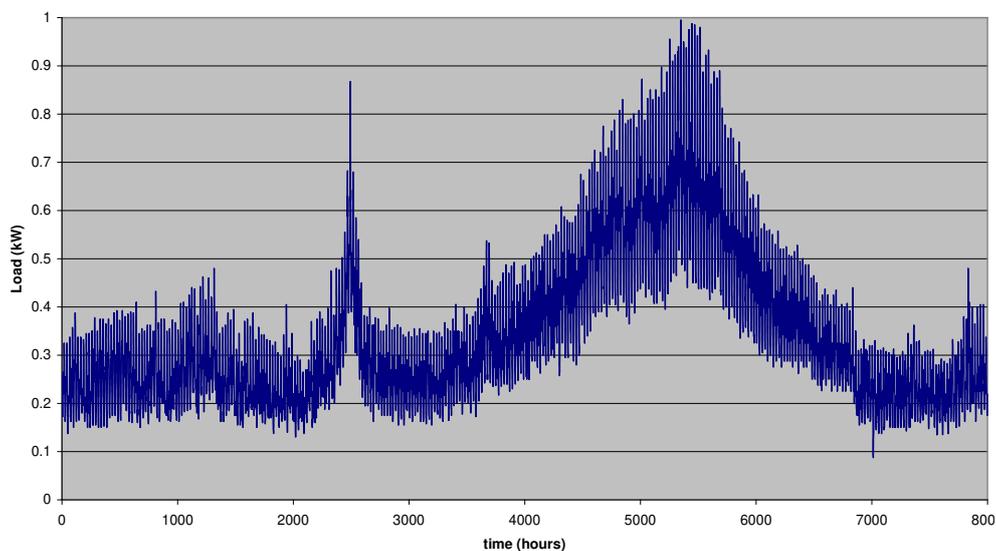


Figure 9 – Load profile (normalized) for a Greek island

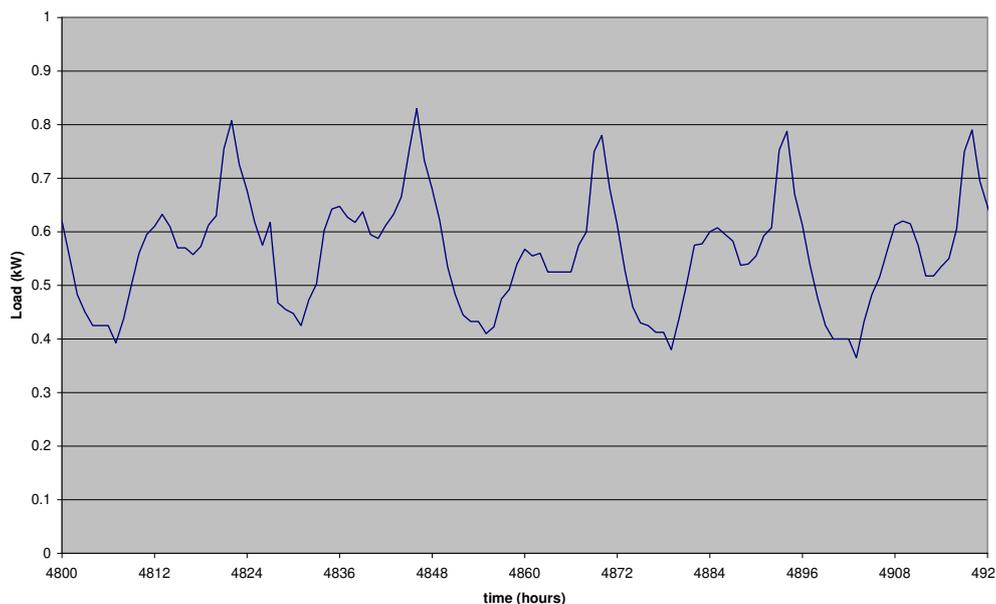


Figure 10 – Daily load variation for a Greek island

6.2 Power System Configuration

The power system modeled included:

- Mini-grid main load with a peak at 4MW (Undispatchable)
- PV generator of 1.5 MW peak (Undispatchable)
- Wind generator of 1 MW (Undispatchable)
- 1 diesel generator 2MW (dispatchable unit1)
- 1 diesel generator 1.5MW (dispatchable unit2)
- 1 diesel generator 1MW (dispatchable unit3)
- 1 diesel generator 0.5MW (dispatchable unit4)
- 1 deferrable load 100 kW (dispatchable unit5)
- 1 deferrable load 50 kW (dispatchable unit6)
- 1 dump load 3 MW (dispatchable unit7)
- 1 battery unit 1MW/4MWh (dispatchable unit8)
- 1 battery unit 0.1MW/2MWh (dispatchable unit9)

6.3 Supervisory Strategies

Two basic supervisory strategies have been tested for validating the simulation platform.

6.3.1 Strategy s1

This is a very simple supervisory strategy, which consists in doing nothing for optimizing the operation. All available power units are switched on all the time and the deferrable loads are not controlled. In case the demand is higher than the renewable energy production, the generators share the positive load according to the frequency value. On the contrary, if the renewable power production exceeds the mini-grid power demand, the dump load and battery units share the negative load. This strategy does not send power setpoints to the dispatchable units and results in high fuel consumption and important frequency deviations.

The corresponding Matlab® Sfunction is: power_dispatch_iea1.

6.3.2 Strategy s3

In Strategy s3, the supervisory unit starts and stops diesel units and deferrable loads based on the last measured load power. If positive power is needed, enough diesel resources are started with a rotating reserve of minimum 500 kW. If negative power is available, all the deferrable loads are switched on, the rest of the power going to the battery storage. The battery storage 1MW/4MWh is kept at a state of charge (SOC) of 75%.

The corresponding Matlab® Sfunction is: power_dispatch_iea3.

6.4 Frequency Variations

Frequency corrections are needed if the power setpoints from the supervisory control are not correct. In Strategy s1, frequency fluctuates from 49.2 to 50.3 Hertz. Frequency corrections are less necessary for Strategy s3.

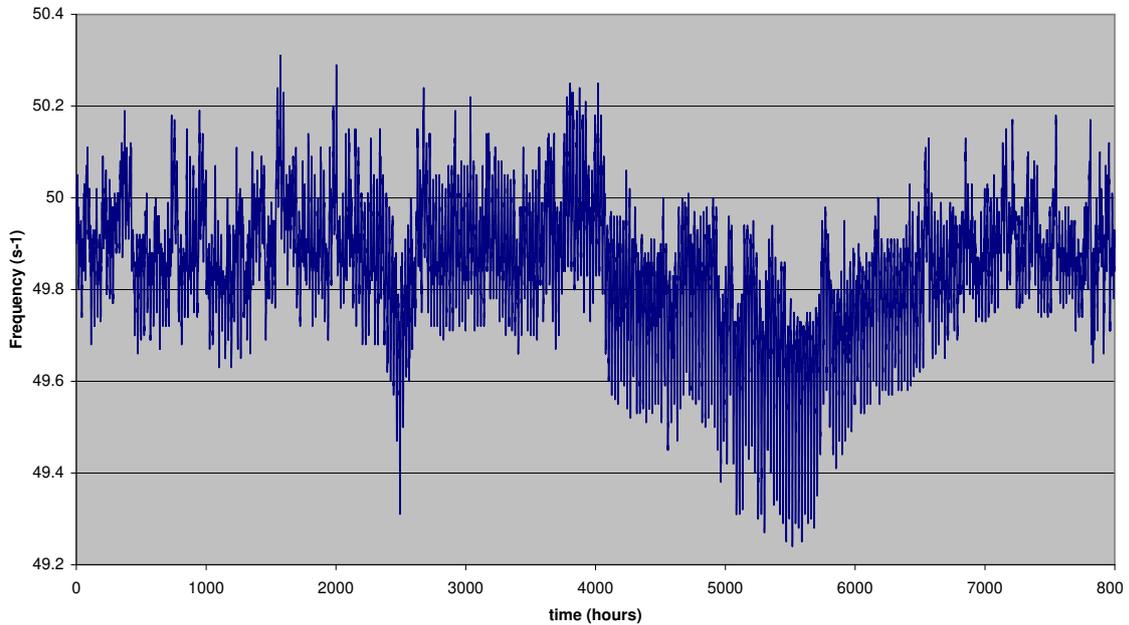


Figure 11 – Frequency variations with Strategy s1

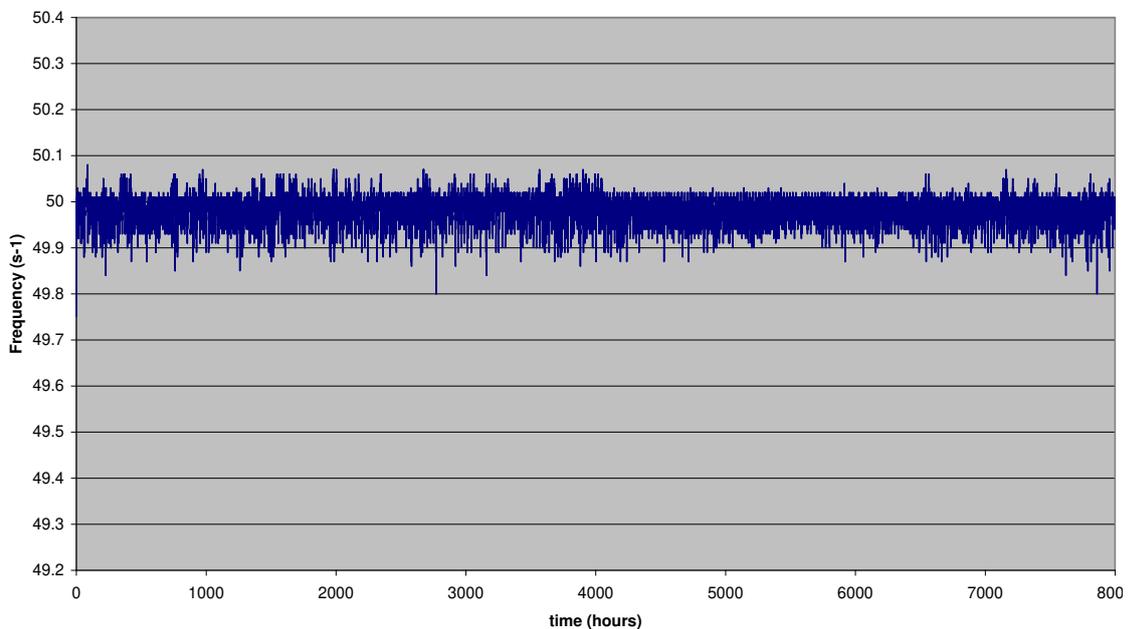


Figure 12 – Frequency variations with Strategy s3

6.5 Annual Production and Costs

The following economic parameters have been used for the simulation:

- Discount rate: 10%
- Fuel cost: 0.8 EUR/liter
- Analysis period: 1 year

Table 1 and Table 2 show the simulation results for the supervisory strategies s1 and s3.

Strategy s3's total cost (= net load cost in the table) is almost 50% of the cost corresponding to strategy s1, mainly due to efficiency gains by avoiding low load diesel genset operation. Diesel1 produces more energy under Strategy s3 than s1, but runs fewer hours.

Although Strategy s3's costs are reduced, they remain expensive and can be optimized.

Table 1 – Results with Strategy s1

	Total Energy	Positive Energy	Negative Energy	Avg Power	Operation	Total Cost	Levelized Cost
	MWh	MWh	MWh	kW	hours	kEUR	EUR/kWh
Net Load	6430.92	6755.34	-324.42	734.14	8759.5	7742.73	1.15
unit1	2748.94	2748.94	0	313.81	7795.75	3047.4	1.11
unit2	2063.65	2063.65	0	235.58	7797.5	2286.09	1.11
unit3	1378.37	1378.37	0	157.35	7800.25	1524.68	1.11
unit4	693.09	693.09	0	79.12	7812.25	763.52	1.1
unit5	-87.55	0	-87.55	-9.99	875.5	0	0
unit6	-87.51	0	-87.51	-9.99	1750.25	0	0
unit7	-194.01	0	-194.01	-22.15	985.75	0	0
unit8	-71.15	45.03	-116.18	-8.12	2453.25	80.69	1.79
unit9	-12.91	10.38	-23.29	-1.47	4501	0	0
PV	2480.15	2480.15	0	283.13	4948.75	0	0
WIND	2724.62	2724.62	0	311.04	6326.25	0	0

Table 2 – Results with Strategy s3

	Total Energy	Positive Energy	Negative Energy	Avg Power	Operation	Total Cost	Levelized Cost
	MWh	MWh	MWh	kW	hours	kEUR	EUR/kWh
Net Load	6430.92	6755.34	-324.42	734.14	8759.5	3873.07	0.57
unit1	5713.53	5713.53	0	652.25	6036.25	2779.61	0.49
unit2	892.27	892.27	0	101.86	1020	453.06	0.51
unit3	445.71	445.71	0	50.88	2222.25	479.2	1.08
unit4	0	0	0	0	0	40.18	0
unit5	-124.15	0	-124.15	-14.17	1241.75	0	0
unit6	-96.88	0	-96.88	-11.06	1937.75	0	0
unit7	-250.37	0	-250.37	-28.58	2420.5	0	0
unit8	-149.21	69.03	-218.24	-17.03	8759.75	80.69	1.17
unit9	0	0	0	0	0	0	0
PV	2480.15	2480.15	0	283.13	4948.75	0	0
WIND	2724.62	2724.62	0	311.04	6326.25	0	0

7. Conclusions

This report provides an overview of the most important parameters for controlling typical hybrid mini-grids. It also discusses the importance of a supervisory control. For typical hybrid mini-grid system design configurations, the most common supervisory strategies are presented.

However, due to the variety and complexity of hybrid mini-grid designs, simulation is an essential tool for assessing the performance of dispatch strategies. Therefore, a simulation tool based on MATLAB[®] software is provided for a deeper analysis of the impact of the different possible dispatch strategies. The tool allows several supervisory control strategies to be simulated and compared economically.

Two selected dispatch strategies have been compared on a virtual case study with the simulation tool. The simulation results indicate clearly the economic benefits of using the most suitable strategy.

8. References

- [1] Manwell J, Rogers A, et. al., Hybrid2 - A Hybrid System Simulation Model: Theory Manual, Renewable Energy Research Laboratory, University of Massachusetts, 2006.
- [2] T. Degner, A. Engler, P. Funtan, R. Geipel, G. Klein, M. Landau, A. Shustov, P. Strauß, M. Vandenberg, et al.: „Modulare Systemtechnik III - Vernetzung modularer Systeme - Netzregelung zur wirtschaftlichen Optimierung dezentraler Energieversorgungsstrukturen mit hohem Anteil erneuerbarer Energiequellen“, Abschlussbericht, ISET, 2005.
- [3] P. Caselitz, D. Lehmkuhl, and B. Panahandeh: “ISET Alternative Power Library-Universal Model Library for Simulation of Decentralised Power Supply Systems”, 2nd European PV-Hybrid and Mini-Grid Conference, Kassel University, Germany, 2003, pp. 456-461.
- [4] J. Jahn, P. Strauß, M. Vandenberg: “Management Strategies and Advanced Inverter Control in Microgrids”, 2nd International Conference on Integration of Renewable and Distributed Energy Resources, 4.-8 December 2006, Napa, USA.
- [5] M. Ibrahim: “Decentralized Hybrid Renewable Energy Systems Control Optimization and Battery Ageing Estimation Based on Fuzzy Logic”, PhD dissertation, Kassel University, Germany, 2002.
- [6] A. de Lemos Pereira: "Modular supervisory controller for hybrid power systems", PhD thesis, Risø National Laboratory, Roskilde, 2000.
- [7] Christian Dumbs: “Development of analysis tools for photovoltaic-diesel hybrid systems”, PhD thesis, Ecole des Mines de Paris, 1999.
- [8] B. Wichert: “Control of photovoltaic-diesel hybrid energy system”, PhD thesis, Curtin University of Technology, Perth, 2000.
- [9] MATLAB® software - <http://www.mathworks.com/products/matlab/>.



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