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DESIGN OF A SMALL-SCALE ENERGY MANAGEMENT SYSTEM TO BE IMPLEMENTED IN DENLAB

BY

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Abstract. The interest in decentralized energy systems with high penetration of renewable sources and combined heat and power technologies (CHP) has increased during the last years. This paper describes current research being developed at DENlab, a Renewable Energy Lab located at the Power Systems Group of the Electrical Sustainable Energy Department of Delft University of Technology. This research is focused on the development of an energy management system (EMS) for small-scale systems with multiple energy carriers, such as heat, gas and electricity.

Key words: energy management system; DENlab; windspeed forecast.

1. Introduction

The energy sector is facing unprecedented challenges in relation to the world's long-term energy supply. The International Energy Agency estimates that between 2010 and 2030 the total primary energy demand will increase by 35% (http://www.iea.org). Developing countries play an important role in this scenario. Furthermore, the predicted depletion of fossil fuels and the need of reducing CO_2 emissions have stimulated scientists to search for more sustainable options, such as decentralized energy systems with a high penetration of renewable sources and combined heat and power technologies.

In order to cope with the demands of these systems, new planning and control strategies are necessary. DENlab is a renewable energy lab that

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facilitates research on small-scale renewable energy systems. This paper is related to current research being developed for DENlab, particularly regarding the design of an energy management system (EMS) suitable for multiple energy carriers, that will be tested in this facility. This paper gives a global overview of the modules that make up the energy management system. More details about each of the modules can be found in the papers that are mentioned in the respective sections. Parts of this paper have been published in the Proceedings of the 6th International Conference on Electrical and Power Engineering, EPE 2010, Iaşi, Romania.

2. DENlab: a Renewable Energy Lab

DENlab is a renewable energy lab located at the Power Systems Group of the Electrical Sustainable Energy Department of Delft University of Technology, the Netherlands. The objective of this laboratory is to serve as a test facility for projects related to small-scale renewable energy systems. Due to the inherent differences when compared to conventional systems, more research is required in technical aspects, such as the planning, control and integration of different energy sources; this kind of studies can be tested at DENlab.

More information about the original setup of DENlab were given by van Voorden *et al*., (2002). DENlab has a power capacity of up to 50 kW. The characteristics of the various components to be included in the system can be programmed in a PLC, which, *via* a Profibus, sends the setpoints to the nine power converters that are physically placed in the lab. In this way, a variety of components can be emulated and the real power flow at the 3-phase autonomous grid at DENlab can be monitored. The currents that flow in the system represent the currents that would flow at an analogous physical system.

3. Energy Management System

The energy management system that is going to be implemented in DENlab consists of three main modules: the forecast module, the optimization module and the real-time control module. This EMS is designed to include high penetration of stochastically changing generation, in this case, wind generation, as well as multiple energy carriers, such as heat, gas and electricity coming from combined heat and power generation. For this reason, the general approach differs from traditional energy management systems.

Fig. 1 shows a schematic representation of the energy management system. Each module is described in the following subsections.

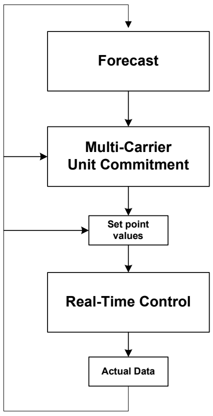

Fig. 1 – Energy management system scheme.

3.1. Forecast Module

The forecast module generates forecasts for load and wind speed time series. Currently, persistence forecasts are used for the load. However a better forecasting method is going to be developed in future works. For the wind speed, a forecasting model was built using measurements taken by an anemometer that is located at the roof of the building where DENlab is located. This forecasting model is described below.

The information on power output from wind turbines for a few hours ahead, due to the stochastic nature of wind, is characterized by high uncertainty in contrast to conventional generation. In the scheduling procedure, wind power has priority and consequently the wind speed forecasts will have significant influence on scheduling the units. Therefore, reliable information about future wind speed values is required.

Forecasting in microgrids is mainly short-term with high temporal resolution for the next 1…4 h (Hatziargyriou *et al.*, 2005). In this work, forecasts will be made every 15 min. for a forecast horizon of 4 h. The requirement is that wind speed measurements have to be made available regularly, *i.e.* at least every 15 min. Whenever a wind speed measurement is recorded, a forecasting model is used to predict wind speed for the next 16 quarters and, in this way, the forecasts made in the previous period are updated.

In order to build the forecasting model, the guidelines for modeling wind speed time series presented by Lojowska *et al.*, (2011) were followed. For this purpose, wind speed time series measurements recorded in October 2006, in DENlab, Delft, the Netherlands, were used in the modeling procedure. The time series comprises minute-based measurements, thus 15 min. averages were derived so that the new time series complies to the unit scheduling frequency. First, the time series was transformed to stationarity by removing features like diurnal seasonalities and non-gaussian distribution. Then, by means of statistical tools, a suitable model in the class of ARMA-GARCH models was specified and tested. The model that was found using good statistical practice is the ARMA(1,2)-GARCH(1,1)-T model and it is presented below:

$$\begin{aligned} &Y_t = 0.99Y_{t-1} - 0.3\varepsilon_{t-1} - 0.09\varepsilon_{t-2} + \varepsilon_t, \\ &\varepsilon_t = z_t\sigma_t, \\ &\sigma_t^2 = 0.01 + 0.66\sigma_{t-1}^2 + 0.23\varepsilon_{t-1}^2, \end{aligned} \tag{1}$$

where Y_t denotes the wind speed at time t and ε_t the innovations or residuals of the time series. Moreover, σ_t^2 is the conditional variance of ε_t and z_t stands for standardized residuals which are independent, identically Student-T distributed with five degrees of freedom.

The model was validated with respect to the main features of wind speed: distribution, autocorrelation and persistence and this resulted in a confirmed adequacy of the model. The forecasting model that was built using the data from October 2006 can be applied to obtain wind speed predictions for any other October (Lojowska *et al.*, 2011). This is possible because wind speed is characterized by annual seasonality and wind speed behaviour does not change significantly from year to year. Fig. 2 presents measurements recorded in DENlab in October 2007 and the 1-step predictions made using the wind speed time series model. We can see that the forecasted values are in a reasonably small distance from the measurements. The forecasts for higher lead time are associated with higher uncertainty and therefore may deviate more from observations.

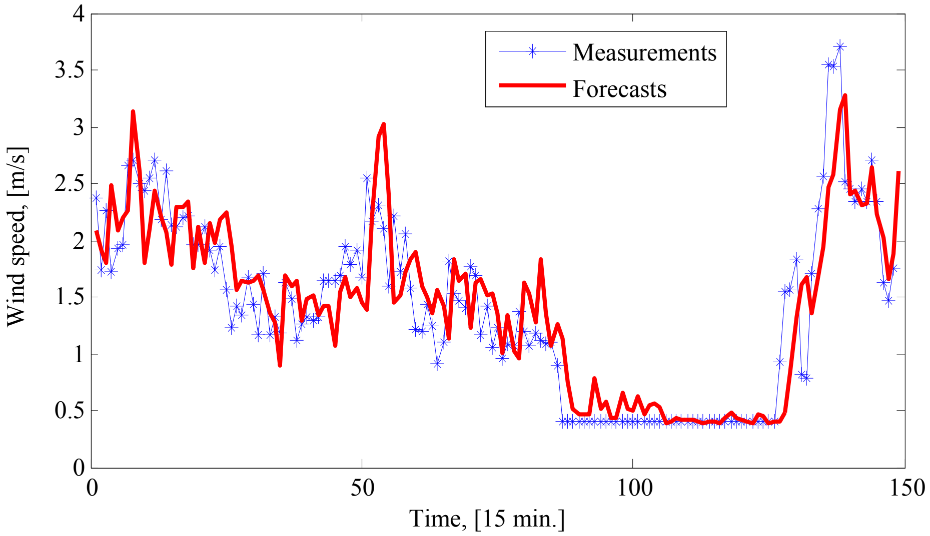

Fig. 2 – Wind speed measurements (October 2007)
and 1-step wind speed forecasts.

3.2. Optimization Module – Multi-Carrier Unit Commitment

The scheduling of the different units is done in order to minimize the generation and operation costs and/or to minimize the CO_2 emissions. Due to the fact that the system includes multiple energy carriers, the *energy hub* concept is applied in order to develop a suitable unit scheduling framework.

The complete description of the energy hub concept can be found in the PhD dissertation *Integrated Modeling and Optimization of Multi-Carrier Energy Systems* (Martin, 2007), which was performed within the project *Vision of Future Energy Networks*. An energy hub is a unit where multiple energy carriers are converted, conditioned and stored (Martin, 2007; Martin *et al.*, 2007; Martin & Göran, 2007). It can serve as an interface for different energy infrastructures and/or loads (Martin, 2007). Fig. 3 shows a representation of an energy hub containing three components. Components *A* and *B* represent combined heat and power units; they produce electricity and heat. Component *C* representes a boiler; it produces heat. The couplings that exist among the inputs and outputs are contained in the energy hub.

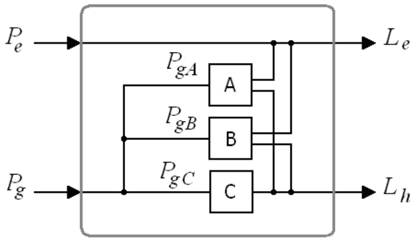

Fig. 3 – Energy hub representation (Lojowska *et al.*, 2011).

Within an energy hub, the input and output power flows are coupled by the coupling factor $c_{\alpha\beta}$ (Martin, 2007), as shown in (1) and the constraint in

$$L_\beta = c_{\alpha\beta} P_\alpha , \tag{2}$$

$$L_\beta \le P_\alpha \Rightarrow 0 \le c_{\alpha\beta} \le 1, \tag{3}$$

where energy carrier, α, is converted into energy carrier, β; P_α and L_β are the steady-state input power and output power of the energy hub, respectively. The coupling factor represents the efficiency of conversion, $\eta_{\alpha\beta}$, but it can also represent a function of the converted power, expressed as $c_{\alpha\beta} = f_\beta\,(P_\alpha)$. For multiple inputs/outputs, a general matrix form can be used (Martin, 2007; Martin & Göran, 2007)

$$\underbrace{\begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{bmatrix}}_{\mathbf{L}} = \underbrace{\begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \cdots & c_{\omega\omega} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{bmatrix}}_{\mathbf{P}}, \tag{4}$$

where $c_{\alpha\beta} = \eta_{\alpha\beta}$ or $c_{\alpha\beta} = f_\beta(P_\alpha)$.

For the unit scheduling the concept of *Multi-Carrier Unit Commitment* is used. This term is defined as the computational procedure for making decisions in advance with relation to which hub elements to start up or shut down and for how long, also with relation to the sequence in which this should be done in order to find the optimal operation for processing multiple energy carriers, while maintaining the power balance of the system (Ramirez-Elizondo & Paap, 2009). More information about the Multi-Carrier Unit Commitment framework and the optimization methodology were given by Ramirez-Elizondo

& Paap (2009). The scheduling module will give scheduling solutions for the coming 4 h in periods of 15 min., as it is done in the forecast module. Some results obtained for the energy hub of Fig. 3 can be observed below. Table 1 contains representative electricity and heat load demands for a random day for the period between 15:45 h and at 18:45 h for a load of 10 households. Table 2 contains an illustrative multi-carrier unit commitment solution, where “1” indicates that the unit is ON.

Table 1
Electrical and Thermal Loads

	1	2	3	4	5	6	7	8	9	10	11	12
L_e	10.1	9.9	7.4	8.5	11.9	14.8	14.6	19.2	19.8	16.3	11.0	5.9
L_h	10.6	22.9	26.4	37.6	52.9	54.1	72.3	87.9	88.2	48.1	32.4	33.3

Table 2
Multi-Carrier Unit Commitment Solution

	1	2	3	4	5	6	7	8	9	10	11	12
Elec. Grid	1	1	1	1	1	1	1	1	1	1	1	1
CHP *A*	1	1	1	1	1	1	1	1	1	1	1	1
CHP *B*					1	1	1	1	1	1		
Boiler *C*								1	1			

When wind generation is included, its forecast is taken into account for the scheduling. The wind generation unit delivers its power without restriction, it won't be subjected to any scheduling, that is, it will remain ON as long as the measured wind speed remains between the operational boundaries. An optimized economic dispatch is calculated with each Multi-Carrier Unit Commitment solution. The results obtained from the optimization module are sent as setpoints for the real-time control module.

DENlab can be operated as a grid-connected or as an autonomous system, thus storage is an important part of the system, specially in autonomous operation. The way in which storage is taken into account for the multi-carrier unit commitment is described by Ramirez-Elizondo *et al.* (2010).

3.3. Real-Time Control Module

At DENlab, real-time data is exchanged with the control system *via* standardized data interfaces. This data serves as input for the control module. The heat flows are completely modeled, since there is no heat infrastructure in DENlab. A microgrid at island operation is a complete power system, yet very small; moreover the functionality associated with system operation such as frequency control must therefore be available, which in such a small system results to be more challenging (Bollen *et al.*, 2009).

As presented by Bollen *et al.* (2009) the following performance criteria for the voltage frequency is considered: the frequency should be situated between 49 and 51 Hz during at least 95% of the time and it should not be less than 42.5 Hz or higher than 57.5 Hz. Regarding the voltage magnitude: the 1 min. rms voltage should remain between 92% and 108% of the nominal voltage, the 1-sec. rms voltage between 90% and 110% and the 1-cycle rms voltage between 70% and 115% (Bollen *et al.*, 2009). A description of the control is given below.

In order to implement an energy management system, the operation of a power system should fulfill technical and economic objectives. The energy management system that was designed accomplishes this task through a process guided by control decisions that are based on constant monitoring of the condition of power system variables. A detailed scheme of the communication interactions between the modules that comprise the energy management system are presented in Fig. 4 with the name of Distributed Energy Management System (DEMS).

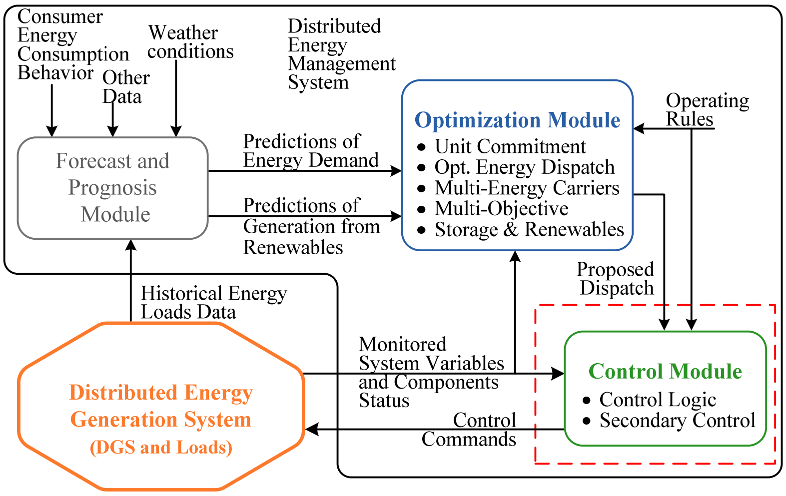

Fig. 4 – Distributed energy management system.

The modular structure of the distributed energy management system is based on the results obtained by Bollen *et al.* (2009). The decision and control of the DGS's operation is accomplished by interactions within the three modules, with the system operator and through acquisition of exterior data. The DEMS operates the components based in the economic objective of cost minimization. As it was mentioned in the previous section, the optimization module proposes a set of setpoints for optimal operation, while it follows the operating rules, including economic, technical and environmental objectives.

The control module makes decisions within the operating rules framework by monitoring the systems variables and components status and by taking the proposed energy dispatch as initial operation points. Therefore, the control logic guarantees adequate commands to govern the energy dispatch of each distributed generation source in order to satisfy the energy demand properly. Fig. 5 shows a schematic representation of the main control that was designed for a system with three CHP units, a wind turbine, a boiler, electricity storage and heat storage.

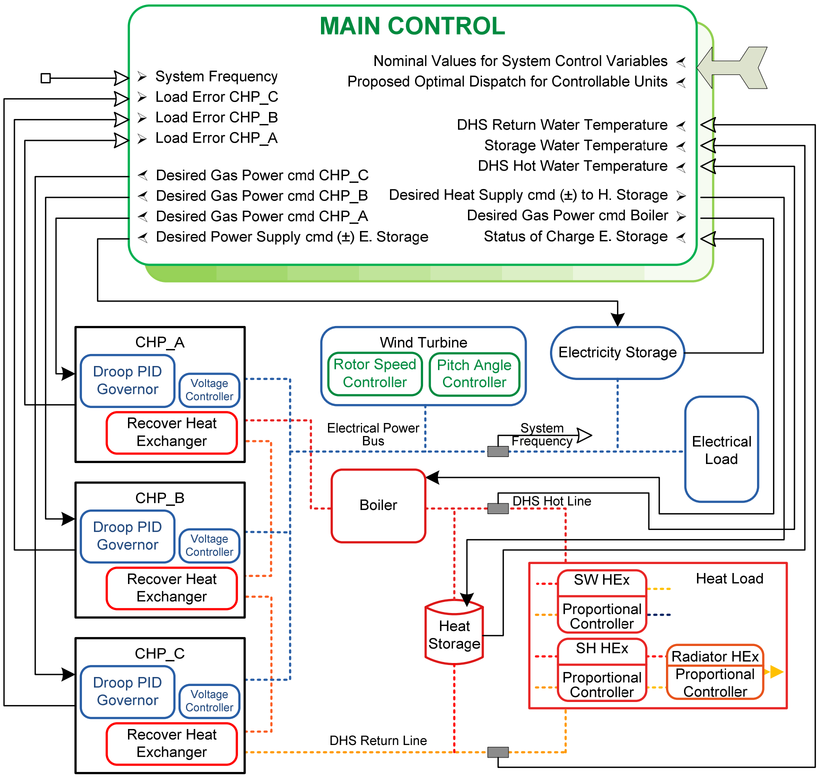

Fig. 5 – Hierarchical real-time control.

A detailed description of the real-time control is given by Vélez *et al.* (2011).

4. Conclusions

This paper gives a global overview of the design of a small-scale energy management systems that will be implemented in DENlab. A forecasting model was developed for the wind speed time series according to good statistical practice. Using a similar methodology the load forecast can be improved as well. Regarding the scheduling module, the *energy hub* concept is used in order to include the coupling of the cogeneration units involved. The real-time control module is still under development for the application in different configurations.

Results for the automated operation of DENlab applying this energy management system will be presented in a future work.

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PROIECTAREA SISTEMULUI DE MANAGEMENT AL UNEI MICROREŢELE DE ENERGIE ÎN CADRUL LABORATORULUI DE SURSE REGENERABILE DENLAB

(Rezumat)

Ultimii ani au demonstrat interesul crescut legat de sistemele electroenergetice alimentate din surse de energie termică şi electrică regenerabile, distribuite. Lucrarea cuprinde rezultate ale activităţii recente de cercetare desfăşurată în cadrul laboratorului de surse regenerabile, DENLAB, din cadrul Departamentului de Energie Sustenabilă al Universităţii Tehnice din Delft, Olanda. Cercetarea a fost orientată către dezvoltarea unui sistem de management pentru microreţele cu purtători diferiţi de energie cum sunt gazul metan, energia termică şi electrică.