Situation-Aware Assessment of Balancing Need and Resource

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***Abstract*—Distributed generation and renewable energy sources are both, new disturbance and new regulation resource. Most renewable energy sources are quite unlike classical power plants but often have capabilities enabling the provision of ancillary services. For example, modern wind turbines could provide limited fast active power reserves, similar to inertia or primary reserves. If considered disturbance or resource, ultimately depends on the system operator's capability to oversee need for and availability of such reserves. Wind power may at times provide a certain share of system stabilization, but it must also be seen that this contribution is limited and that it fluctuates with the available wind. Moving toward the design of tools that may provide such information, this paper proposes a functional modeling approach to identify situational control requirements for a power system with a high share of fluctuating energy resources.**

***Index Terms*—Wind Power, Ancillary Services, Functional Modeling, Power System Control, Distributed Resources**

I. INTRODUCTION

From a power system control perspective, distributed generation and renewable energy sources can be either, an additional disturbance and a new regulation resource. On the one hand available resources are fluctuating, but on the other hand control capabilities, for example of modern wind turbines, are not fully utilized. The role these resources may assume depends on the way a system operator can asses the availability of and need for specific control functions. Despite the capability of these resources to provide a number of ancillary services [1], and coordination technologies [2], such as virtual power plants, the present operation paradigms make it difficult to utilize these resources. Typically regulating resources have to be scheduled ahead of time in a way that ensures the availability of regulating power for all expected situations.

Considering the strong variations of system conditions in power systems with a very high share of wind power, this traditional approach may be very conservative and ineffective. One of the main barriers in the way of a more effective utilization of the above listed resources is the problem of visibility to operators. Recent advancements in control room design lead the way to better controllability of wind farm clusters with respect to voltage control - for "operating wind farms like power plants" [3].

Yet, new tools are needed that enable an overall assessment of balancing resources [4] in the system. As renewable energy sources have a very different character than typical thermal power plants, naturally the understanding of the control situations in a system with a large penetration of such resources must be quite different. Wind power itself may in fact provide a certain share of system stabilization, but it must also be seen that this contribution is limited to only a part of the required functions.

The approach proposed in this paper is used to analyze more fundamentally the question, which kind of information is required to improve situation awareness of operators from a control perspective. In Section II an approach to the qualitative assessment of control situations by functional modeling is introduced. Section III describes system balancing as a control problem and illustrates the application of the functional modeling. A small simulation example in Section IV uses the understanding gained from the previous modeling to reason about a control situation with respect to secondary control, with wind power and islanding. Section V concludes.

II. MODELING OF CONTROL SITUATIONS

The term control situation here is understood from a perspective of supervisory control. For example a system operator needs to asses the ability of the controlled system to achieve its control objective. Here, an operator needs to be able, not only to evaluate the current performance of the system against performance requirements, but also to anticipate and to secure adequate resources (control means) for future disturbances. According to [5], a control situation is composed of information about

1) Control requirements. What is the expected disturbance level and the needed performance?
2) Control possibilities. What reserves are or could be made available?

With varying outer system conditions, both, system needs and the availability of control means, may vary.

Applied to a power system with a very high share of fluctuating energy resources, the control situation with respect to frequency control is composed of elements of primary and secondary control, but also of the availability regulating reserves, that may be acquired through a realtime marketplace. Usually these different elements of the situation are attributed to largely independent domains, such as control and HMI design, prediction, bidding, market design, etc.; each domain has its own representation of the system.

Yet, the "types of goods"(usually referred to as energy or ancillay services) that are to be traded on such markets, as well as the terms of their delivery, need to be specified on the basis of technical understanding. The result is an interdependence

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realized through the specification of mutual requirements. For example grid-aspects determine voltage levels and interconnector capacities, purely from an electrical perspective; from a control perspective, those values may be considered as control objectives or constraints; yet, from a market point of view, both transmission capacities and control reserves can be considered trading goods (services).

In a heterogeneous energy system, this network of interdependent interests and tools determines the overall system behaviour[1]. However, at a point where the overall system is challenged architecture is challenged, as it is with the integration of very high shares of wind energy, it is not sufficient to study the behaviour alone. Here it is important to consider interests, needs and provided functions, in order to identify underlying assumptions and possibly to redesign parts of the system.

Interests and functions are connected as ends and means. A methodology capable of formalizing means-ends levels and functional relations will be presented and employed in the following to study the implications of such high-fluctuation scenarios in a given power system architecture.

Ultimately, a tool that assists an operator needs to quantify requirements, however, simply asking for quantification is not enough as the real difference between a functional representation and plain physical facts (numbers) is its ability to provide a meaningful context.

The question in case of control requirements becomes: What information do you need to draw proper information to generate models needed for control? Functional modeling provides a meaningful context for control actions. The context of control actions is the process they work for and with.

A. *Functional Modeling with MFM*

Multilevel Flow Modeling (MFM) is an approach to modeling goals and inter-connected functions of complex processes involving interactions between flows of mass, energy and information (Lind 2005). It provides means for a purpose-centered (as opposed to component-centered) description of a system's functions. MFM enables modeling at different levels of abstraction using well-defined means-ends relations and whole-part compositions (Figure 1b). Process functions are represented by elementary flow functions interconnected to form flow struc-tures which represent a particular goal oriented view of the system (Figure 1a). The views represented by the flow structures, functions, objectives and their inter-relations together comprise a comprehensive model of the functional organization of the system represented as a hypergraph. MFM is founded on fundamental concepts of action and each of the elementary flow and control functions can be seen as instances of more generic action types.

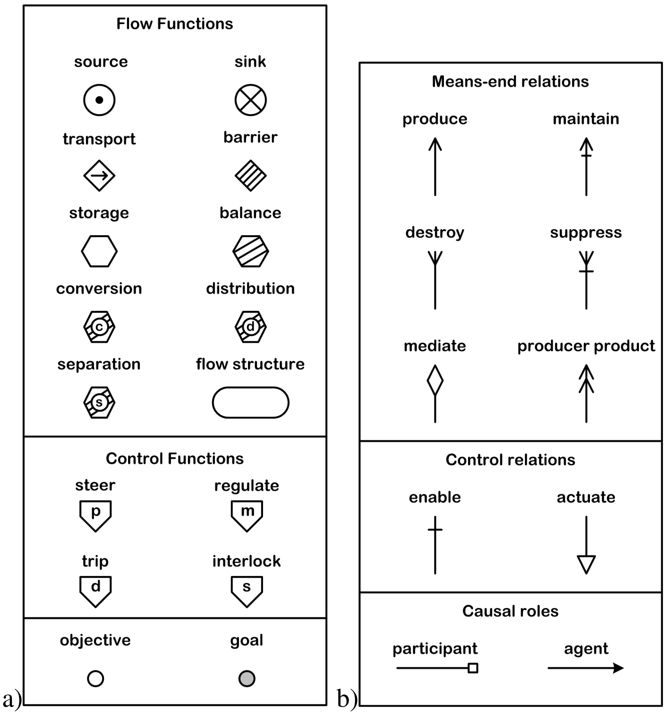

Fig. 1. a) the box on the left lists the MFM-symbols, elementary flow- and contol-functions as well as the flow structure, which combines an interconnection of functions (MFM entities); b) the right box presents all MFM relations and the symbols for objectives and goals (MFM relations).

Models created in MFM are a formalized conceptual representation of the system, which support qualitative reasoning about control situations. MFM is supported by knowledge based tools for model building and reasoning. MFM models can be and have been employed for the purposes of state identification (and representation) and action generation. State identification applications include:

- model based situation assessment and decision support for control room operators
- hazop analysis
- alarm design and alarm filtering

For action-generation, it has been shown that MFM-models can be used for

- deriving action sequences for startup, and
- planning of control actions (counter-action planning)

Further possible applications include operator support systems or integrated HMI and process-design. MFM has been used to represent a variety of complex dynamic processes, i.e. in

- fossil and nuclear power generation
- chemical engineering (e.g. oil refineries) and biochemical processes.

The method was originally conceived in the context of cognitive systems engineering as an intermediary model for work domain analysis, but has been developed into a method in its own right[2]. Its strong semantic concepts and existing software tools make it suitable for integration with modern methods of intelligent control [7]. Current research in MFM focuses on the improvement of its representation power for electric energy systems, integration with multi-agent frameworks, and automatic fault-tree generation.

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[1] Dynamic aspects of this combined behaviour have been studied for example in [6]

[2] For more resources on MFM, its underlying principles and its applications, please contact the author.

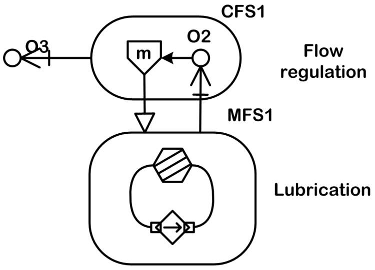

Fig. 2. MFM model of the regulated lubrication system

These diagrams model the relations between different types of information that can be acquired, for example from measurements. Even if measurements are incomplete, it can be inferred on the basis of these relations, which and how other functions would be affected.

1) Modeling example for control functions: In MFM system functions are represented by combinations of flow-structures (e.g. representing the intended energy-flow process in a system) and control-structures, which model purpose and function of control systems. Control systems are used for ensuring that process objectives are met in spite of uncertainty and disturbances in the process. The example in Figure 2 illustrates a simple controlled circulation process, combining a mass-flow structure with an energy flow structure.

The example shows a controlled pump-lubrication process which is part of a larger process involving water circulation for heat transfer: In order to avoid circulation-pump problems, the lubrication flow in the pump needs to be kept within specified limits. An engineering solution to this problem could be to use a regulator measuring the oil flow and controlling the speed of the oil pump. The function of the regulator is to maintain oil flow within limits. This function can be modelled in MFM as shown in Figure 2.

Note that there are two objectives here: O2 and O3. O2 (“keep flow within limits”) is "process" objective defining the purpose of the control system with respect to the lubrication-flow. In contrast, O3 specifies the performance required of the regulated process, as for example stability margins or maximum time constants see also Lind [8].

The remainder of this paper aims at illustrating how this type of model is be useful to represent and understand different control situations in balancing of a power system with fluctating resources and an interconnection.

III. SYSTEM BALANCING: REQUIREMENTS AND RESOURCES

System balancing is essentially a control problem, where regulating power is provided and utilized to achieve an almost constant frequency. The control objective in frequency control is a dynamic balance betweend the power fed into the system and the power that is consumed, which, by the strong electromechanical interactions between synchronous generators[3], is reflected in the system frequency.

In different power systems the coordination and control of active power supply is handled differently. In principle, two types of balancing have to be distinguished: First, “reactive” control with the purpose of maintaining and recovering system balance for contingencies and unpredictable load and generation variations; Second, the “preventive” control measures that aim at steering the power system through predictable variations.

The scheduling of control reserves connects both types of control functions on the generator-side. However, from a system operator perspective these two ways of providing power are very different functions. The connection is often established through different types of markets where generators can bid their capabilities to provide one or another function. In the following we ignore the market function and therefore there is no need to distinguish individual generators, but instead to merely focus on the function provided. This focus on functional purpose becomes particularly important when we consider the inclusion of balancing functions provided non-sychronous generators.

A. Functional Model of Frequency Control

Common to most systems is the frequency droop-control (also primary control). Functionally, the next control level aims at restoring the system frequency by adjusting active power set points of generators, which is handled in a variety of ways in power systems across the globe.

Functional models for the balancing control of power systems have been developed in [9], [10]. The focus has been on the modeling of traditional primary, secondary and area controls (as employed in the UCTE synchronous area). In particular, abstract representation of the controlled systems and representations of primary and secondary control functions have been developed. In this section we review a simple model of the control functions primary system structure, also to introduce to the MFM modeling concept.

Figure III-A shows the MFM model developed in [9], but with an extension to include uncontrollable generation and controllable demand as separate energy sinks and sources.

The energy flow structure models the energy flow from energy generation (energy source on the left) to demand (energy sink on the right). Flow direction is indicated by the arrows in the transport functions. The energy storage in the center represents the aggregated inertia of the system. Note that the links between functions indicate the flow of causal influence between neighbouring functions, which can be directed either with or against the flow of energy. This flow structure models the understanding of the power system that forms the basis for frequency control. Now, frequency control is the mechanism that utilizes this representation and aims at by representing achieving objectives O1a (frequency-droop) and O1b (frequency-restoration).

The control structures S2 and S3 represent the control mechanisms that have the purpose to maintain their control objectives o1a and o1b, respectively. Control structures combine an objective with a control function (here “maintain”).

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[3] Process and control functions that enable this synchronism are functionally subordinated, i.e. they enable the functional representation used on the level of abstraction necessary to represent frequency control. They are therefore considered as a given in this paper. However, their functionas could be integrated using the same modeling technique.

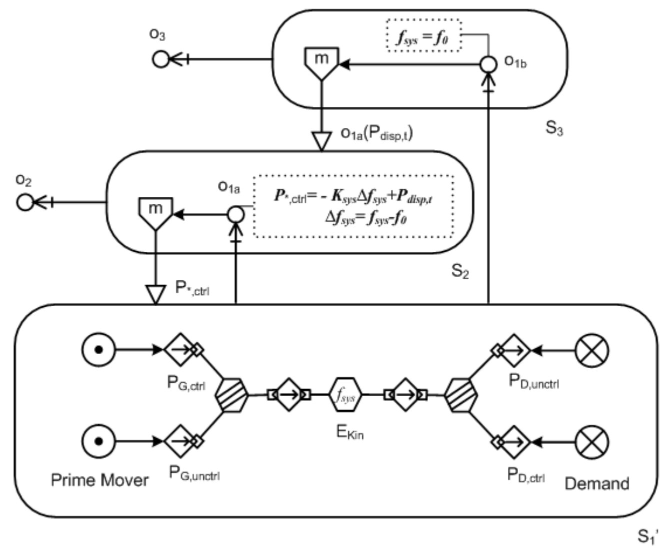

Fig. 3. Aggregated functional model of primary and secondary frequency control of a one-area power system, seperating sources and sinks of controllable/uncontrollable generation/demand. This model assumes that controllable demand is controlled in the same fashion as controllable generation.

This control function is connected via actuate relation. To its control means: in one case (S2) it refers to the energy source in the flow structure below, in the other case (S3), it refers to to the objective in the control structure below.

Each control structure must have an objective, which can be called the "performance objective" of the control structure.

Together these control structres form a cascaded type of control pattern. A combined cascaded and parallel control pattern is formed, is the system is structured into control areas, as illustrated in Figure 4.

IV. EXAMPLE WITH FLUCTUATING GENERATION

The concepts inroduced in the previous sections shall be illustrated on a simple example. Consider a power system consiting of two parts: 1) "Mainland" with large conventional generation (2* 1000MW); and 2) "Renewable island" with 200MW of conventional generation and a wind farm with a nominal capacity of 150MW. An interruptible interconnection couples these two systems. The system has primary and secondary (AGC) control functions as modeled in Figure III-A. For the dynamic simulations, this system is excited by the input signals displayed in Figure 5.

Following the modeling presented in the previous section, all relevant measurements should be those associated with the modeled functions. In short, if the operator is interested in frequency control in general, he should be able to see frequency as one observable, and the input powers demanded of primary and secondary frequency control as a representation of the actuate relations.

This information is given in Figure 6.

This information should be augmented with information about control possibilities, i.e. available reserves and expected

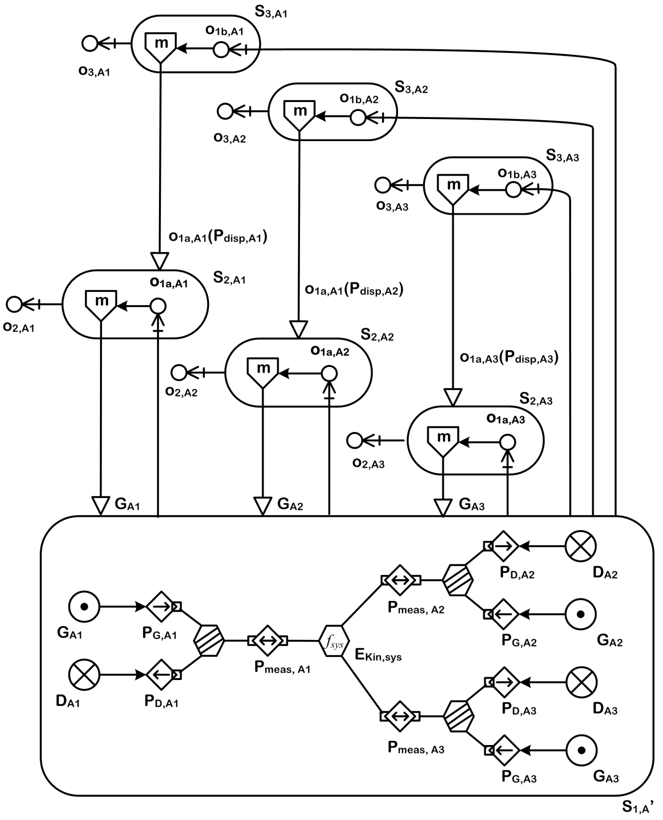

Fig. 4. Control areas are meant to devide the balancing responsibility by accounting measuring exchange and with different objective for the frequency restoration.

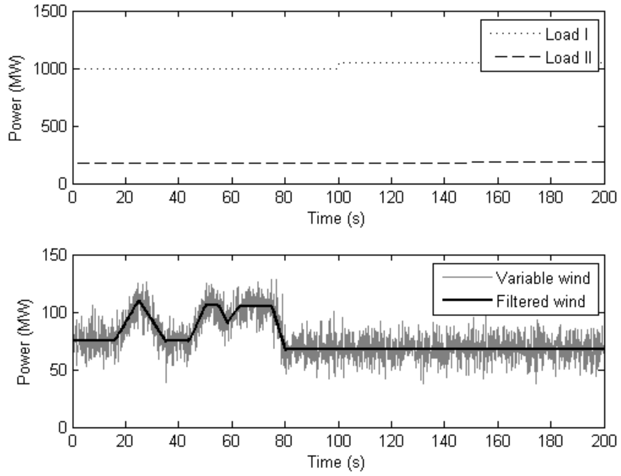

Fig. 5. Input signals for dynamic simulation. The simulated wind power input is composed of a random noise that is added to signal in a sequence of ramping events.

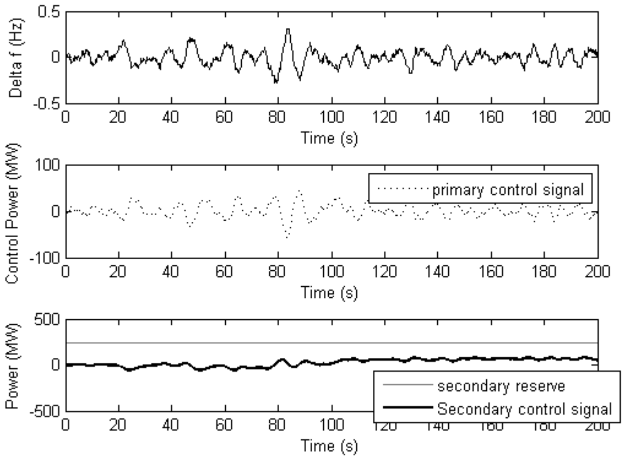

Fig. 6. The time series of relevant control system observables - for the variable wind energy input.

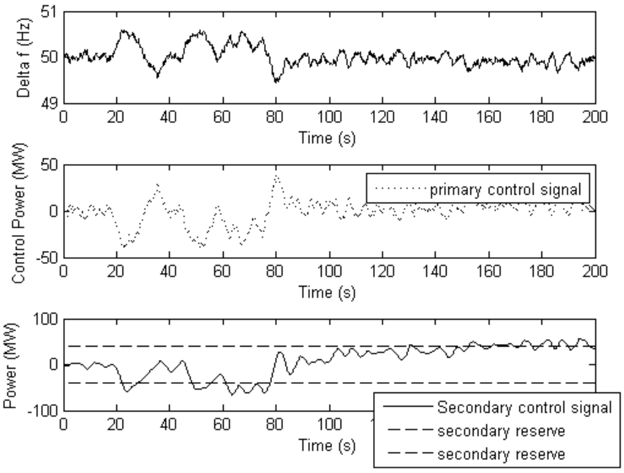

Fig. 7. Frequency and control signals in the islanded situation. The simulated secondary response clearly exceeds the available reserves.

control requirements (determined from expected variability of wind generation).

As can be seen form the plots above, the situation is not critical, and sufficient reserves are available in for the whole time interval. Another situation sets in, when the connection to mainland is interrupted and suddenly the fluctuating wind power needs to be balanced entirely by the remaining smaller power plant. Clearly, the result is that available resources are exceeded.

However, both the power plant and the wind farm can provide resources to resolve the situation.

A range of technically feasible control capabilities of modern wind turbines have been studied recently. Both technical operation ranges e.g. [11] and theoretical stability margins [12] have been studied. It has been shown that a temporary active power overproduction (and underproduction) of a wind turbine is feasible. This active power control range can be used emulate classical power system functions, as for example to

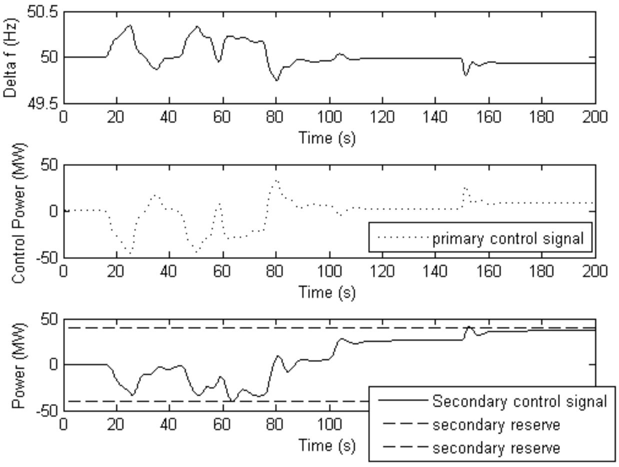

Fig. 8. Remedial actions taken to contain need for secondary reserves in normal range. The power filtering function has been activated to avoid excitation of the generator control system and the generator droop constant (primary control) has been adapted. In by these means, the secondary control need is just kept in the range.

“simulate inertia” i.e. fast active power injection, proportional to the frequency gradient. However, it can also be conceived that the active power injection could be based on other system needs, for example to actively minimize frequency deviations.

For the simulation here, we consider the idea of “power filtering”, i.e. the active reduction of short-term fluctuations by the wind farm itself.

Figure 8 shows the simulation result after remedial actions have been taken.

The functional representation is intended to frame the understanding of possible new control functions - without a complete re-invention of the power system control architecture.

V. CONCLUSION

It has been illustrated above how a functional modeling approach enables a contextual understanding of measurements. The main idea is that a different type of modeling, describing abstraction and control levels in semantic relations rather than in signal diagrams will lead to a clearer framing of control situations. Key to this approach is the underlying shift from mainly numeric representation of control systems to an integrated symbolic representation, which brings (measurement) into the context of its application.

REFERENCES

[1] M. Braun, “Technological control capabilities of DER to provide future ancillary services,” *Distr. Energy Resources, Int. Journ. of*, vol. 3, pp. 191–206, 2007.

[2] M. Braun and P. Strauss, “A review on aggregation approaches of controllable distributed energy units in electrical power systems,” *Distr. Energy Resources, Int. Journ. of*, vol. 4, no. 4, pp. 297–319, 2008.

[3] K. Rohrig, B. Lange, A. Gesino, M. Wolff, R. Mackensen, J. Dobschinski, A. Wessel, M. Braun, C. Quintero, J.-L. Mata, and R. Pestana, “Wind power plant capabilities Ů operate wind farms like conventional power plants,” in *Proceedings of the European Wind Energy Conference (EWEC) 2009*, 2009.

[4] M. Lind, T. Ackermann, P. Bach, H. W. Bindner, Y. Chen, R. Garcia-Valle, M. Gordon, K. Heussen, P. Nyeng, A. Saleem, P. E. Sørensen, M. Togeby, I. Vlachogiannis, S. You, and Z. Xu, "Ecogrid.dk phase I WP2 report - system architecture," Energinet.dk, Tech. Rep., 2008.

[5] J. Petersen, "Control situations in supervisory control," *Cogn Tech Work*, vol. 6, pp. 266–274, 2004.

[6] F. L. A. et al, "Stability analysis of interconnected power systems coupled with market dynamics," *Power Systems, IEEE Transactions on*, 2001.

[7] A. Saleem, K. Heussen, and M. Lind, "Agent services for situation aware control of electric power systems with distributed generation," in *Proceedings of the IEEE PES General Meeting 2009*, 2009.

[8] M. Lind, "Modeling goals and functions of complex industrial plant," *Applied Artificial Intelligence*, vol. 8, no. 2, pp. 259–283, 1994.

[9] K. Heussen, A. Saleem, and M. Lind, "Control architecture of power systems: Modeling of purpose and function," in *Proceedings of the IEEE PES General Meeting 2009*, 2009.

[10] K. Heussen and M. Lind, "Decomposing objectives and functions in power system operation and control," in *Proceedings of the IEEE PES/IAS Conference on Sustainable Alternative Energy, Valencia*, 2009.

[11] G. C. Tarnowski, P. C. Kjær, P. E. Sørensen, and J. Østergaard, "Study on variable speed wind turbines capability for frequency response," in *Proceedings of the European Wind Energy Conference (EWEC) 2009*, 2009.

[12] B. G. Rawn, P. W. Lehn, and M. Maggiore, "Control methodology to mitigate the grid impact of wind turbines," *IEEE Trans. on Energy Conversion*, 2007.

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