CHEMICAL ENGINEERING TRANSACTIONS

VOL. 46, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Peiyu Ren, Yancang Li, Huiping Song

ISBN 978-88-95608-37-2; **ISSN** 2283-9216

DOI: 10.3303/CET1546142

Functional Representation of Integrated Wind-Water Desalination Control System

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In this paper, we propose an approach based on generic component model to realize the functional representation for integrated wind-water desalination control system. This is a component–oriented method. Two elementary notions, the service and the operating mode, are introduced to construct a hierarchical system and to assure the coherences between specification and realization at each level and between levels. An integrated wind-water desalination control system is studied as an application.

1. Introduction

The available clean and potable water is very important for all people, regions and countries. But not all regions have naturally available water sources of sufficient quality and in some particular locations, the desalination is the only option for supplying freshwater, although it is an energy-intensive process (Absar and Belhamiti (2013), Liu and Persson (2013), Nair and Kumar (2013), Xenarios et al. (2013)). The energy-intensive problem tends to limit the desalination applicability to the underdeveloped countries. It is necessary to exploit an effective, local, and available renewable energy resource to reduce desalination production costs (Moser et al. (2013), Mousa et al. (2013), Palacin et al. (2012)). The benefits would certainly include an improvement in the reliability of water supply and a reduction in environmental impacts associated with conventional desalination. Wind power is now a good choice for offering the most economically viable renewable energy source. The main challenge is to combine this fluctuating wind energy supply with the membrane desalination systems to provide an effective and affordable water supply system. We should find an effective method to design this kind complex system (Aström et al. (2001)).

The Generic Component Model (GCM) is an efficient method that can describe components from a functional point view of the users, who receive services and can use them differently in different operating modes (Hu et al. (2006), Staroswiecki and Bayart (1996)). The wind-water desalination control system has several different operating modes according to the running conditions of wind turbine and desalination membrane. This functional method can analyse the combinations of these running conditions to decide the suitable operating mode under the fluctuating wind energy supply. Component interconnections are taken into account by considering higher level components, which result from the aggregation of lower level ones. Staroswiecki and Gehin (1998) present an approach of modelling of a distributed architecture based on the Cartesian products of components. As mentioned in these researches above, the GCM based functional representation relies on pre-designed alternative control structures. The main obstacle to perform these multi-choices tasks is the combinatorial explosion of the products of numerous components, particularly for pre-designing alternative control structures in a large-scale system. The model aggregation is a useful method by which a large-scale system is built as a hierarchical system composed of interacting subsystems (Blanke et al. (2003)). Each subsystem or module involves only a few components and is therefore easy to design, analyse and maintain, but a global objective of the system must also be maintained so that the low modules can be coordinated to attain certain desired objectives. In this paper, our goal is to realize model aggregation for complex control and to present a systematic procedure for the model aggregation of a hierarchical system with a wind-water desalination control system example. This procedure finds its justification from the coherence it achieves in a level and between levels, unifies the two elementary notions service and the operating mode during the model aggregation, and produces the important information about complex control.

Please cite this article as: Hu H.X., Hu Q., 2015, Functional representation of integrated wind-water desalination control system, Chemical Engineering Transactions, 46, 847-852 DOI:10.3303/CET1546142

The paper is organized as follows. We firstly define the necessary notions of generic component model, the services and the operating modes; secondly present an aggregation procedure for a hierarchical system; thirdly we introduce the wind-water desalination control system example. Finally, we provide a brief summary of this paper.

2. The functional representation

This section introduces the two main notions of the GCM: the services and the operating modes which consider firstly the components of the lowest level called elementary components (components that cannot be decomposed into other components). From the user viewpoint, a system component provides one or several services. A service is defined as a procedure whose execution results in at least one modification of its output interface.

A service is run either on the reception of its specific request (for example, close, open for the valve) or permanently in time without any specific request presented to the component (for example: the storage service which is systematically provided by the tank, at all times and whatever the values of the inputs and outputs). The realization of a service rests on hardware/software resources (a tank with no leak for the storage service, a non-faulty sensor for the measurement service ...). The service cannot be delivered when any of these hardware/software elements is not running properly; this is why they are called resources. Therefore, the model associates with each service the set of resources that are necessary for its normal running. Formally summarizing the set of services provided by a component is defined as follow.

Definition 1: The set of services associated to a component is:

$S(k) = \{s_i(k), i \in I_s(k)\}$

$s_i(k) = \langle cons_i(k), prod_i(k), proc_i(k), rqst_i(k), res_i(k) \rangle$

Where S (k) is the set of services of component k, Is the set of indices of the possible services, and the others are straightforward.

The notion of Operating Mode (OM) allows organizing the set of services into coherent subsets taking into account these two following requirements: (1) at a given time only a part of the services provided by a component are required to achieve the objectives linked to this component (for example, some objectives are regulation, initialization …); (2) for safety reasons, incompatible services (for example, initialization and production services) must not be run simultaneously.

So, the notion of operating modes can be used to ensure that the aggregated model is effective in the sense of achieving specifications given either for the higher level model or for the lower level one. An operating mode is a subset of services of a component. The set of operating mode covers the set of services, i.e. each service belongs at least to one operating mode, and each operating mode contains at least one service.

Definition 2: An Operating Mode (OM) is defined by two elements:

1. One or several objectives to be achieved $O_j = \{o_j\}$.
2. A subset of the services of the component $S_j \subset S$ allowing the realization of the objectives.

The automaton of operating modes. Note that a component or a system is always in one and only one OM at the execution time. So the OM of a component can be described by a deterministic automaton given by definition 3.

Definition 3: The operating mode automaton associated to a component is defined by A (M, T, m°) where:

$M = \{m_i\}$ is the set of the OM, each of them being a vertex of the automaton,

$T = \{t_{ij}\}$ is the set of the transitions, each of them being defined by $t_{ij} = \{m_i, m_j, c_{ij}\}$ where mi is the origin OM, m_j is the destination OM and c_{ij} is the firing condition defined from the requests associated to the services belonging to the destination OM.

$m° \in M$ is the initial mode, i.e. the mode where the system stays at its initialization.

3. Building Systems from Components

System architectures can be described at different hierarchical levels. Sensors, actuators, process components are at the field-level. High level components can be built from the aggregation of lower level ones at any hierarchical level. The decomposition of a system to several subsystems and so on until the elementary components can be represented by a pyramidal architecture. Since it may be advisable to allow some components to belong to several subsystems, the structure is not purely hierarchical but is a pyramidal one (Figure. 1). In a pyramidal architecture, each component of level l-1 belongs to at least one component of level l and any component of level l includes at least one component of level l-1.

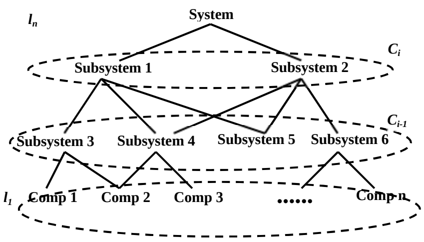

Figure 1: Pyramidal structure of a system

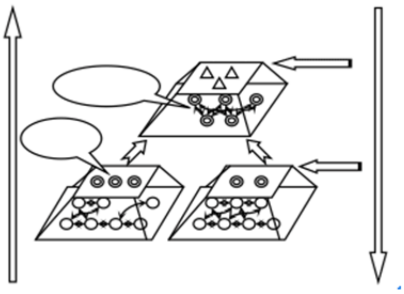

Figure 2: The aggregation of a hierarchical system

Let $S_\alpha(a)$, $O_\alpha(a)$ (resp. $S_\beta(b)$, $O_\beta(b)$) be the services and the objectives associated to the component a being in the mode α (resp. the component b being in the mode β). S_α (a) (resp. S_β (b)) allows the realization of O_α (a) (resp. O_β (b)). Let c be a component of level l which aggregate the components a and b of level l-1. The combination of operating modes α and β, if it is consistent from a view point of user, provides a service of the component c. More generally, we will say that the set φ of the potential services of the component c is the Cartesian product of the operating modes offered by a and b.

$\varphi = \{\Delta = \alpha \times \beta$, such as $\alpha \in M$ (a), $\beta \in M$ (b)$\}$ (1)

Of course, not every combination of lower level OMs is significant or allowed in real practice, for example associate a Test_OM with a Regulation_OM may be not relevant for the application realization, and such a combination should be removed from φ. Moreover there may exist combinations which have the same functional interpretation. Removing irrelevant services from φ allows specifying the set of relevant services φ_r which has to be organized into consistent OMs. Note that it is designers who indeed determine φ_r from φ and structure φ_r into OMs. Defining φ and φ_r and structuring φ_r into OMs constitute the three steps of the aggregation procedure.

This procedure finds its justification from the coherence it achieves in a level and between levels. Removing irrelevant services from the set of possible combination of lower level components' OMs and organizing the set of relevant services into OMs allows guaranteeing the coherence between the available services and the objectives to achieve. In other words, it is a mean to express the relation of "what the aggregated component could do" and "what it should do". Defining the services of a higher level component from the OMs of the components it aggregated and then structuring them into OM through the objective notion allows taking into account a specification given in a hierarchical way, assuring a coherence between levels and decreasing the number of combinations at each level of aggregation.

We can say that the operating mode is a bridge connecting the services available and the objective to achieve in the current level and is also a bridge joining the lower levels and the higher ones in a consistent way. Relations between OMs, objectives and services through the different levels are expressed by the Figure.2.

4. The wind-water desalination control system

The main challenges associated with the use of wind turbines in directly-connected membrane systems are the intermittency and fluctuations of the wind resource which occur due to turbulence and gusts over short periods of time (seconds to a few minutes) and mass air movements over long periods of time (tens to hundreds of hours) (Manwell et al. (2010)), because the Reverse Osmosis (RO) membranes are designed to operate under constant operating conditions with no abrupt pressure or crossflow variations in order to minimise the potential for excessive mechanical stresses on the membrane module. Moreover, the direct connection of a wind turbine to a RO system with no form of energy storage will inevitably result in large fluctuations in pressure and/or flowrate (Miranda and Infield (2003)). Fortunately, using batteries as energy storage is an effective method of buffering short term wind speed fluctuations to provide steady-state performance and improve the productivity of RO-membrane systems. So we present considerable wind-water desalination systems as Figure.3 showed. The wind turbine provides a three-phase variable-voltage variable-frequency power to the whole system. A converter is made of a controlled full wave rectifier and an inverter. The three-phase AC power is firstly rectified by a rectifier, creating a variable-voltage DC power, and then it is returned as required AC again by the inverter. If the wind generating capacity is larger than the load, the storage battery can be charged by the bi-directional inverter. All the pumps of desalination are driven by the power from the converter. The block "Reverse Osmosis Modules" represents an array of parallel connection modules each of which can be running independently.

As mentioned above, the intermittency and fluctuations of the wind is in conflict with the design principle of RO membranes. As with many materials, membranes experience plastic creep under constant pressure and temperature conditions; therefore the combination of fluctuating pressure and flowrate with cycling on/off is expected to cause material fatigue. An upper limit should be applied to the cycling on/off frequency of the membrane system to prevent deterioration of membrane system performance and lifetime. Moreover, the reduction in permeate quality is caused by low flux combined with the continual diffusion of salt across the membrane during a period of intermittency. It is necessary to study and quantify the overall impact of fluctuations or intermittency on RO-membrane system performance. The concept of a safe operating window for the transient operation of RO membrane systems with wind power was first proposed by Feron (1985).

The main aim of determining the safe operating window was to highlight the physical constraints to the safe operation of the membrane system. The knowledge of these constraints and how they impact on performance are useful for designing effective control systems and ensuring efficient operation of RO-membrane systems. The constraints arising from the membrane characteristics that define the safe operating window are illustrated in Figure.4. These constraints were determined to be as follows:

(a) Maximum Feed Pressure -determined by the membrane mechanical resistance;

(b) Maximum Concentrate Flow Rate - should not be exceeded to avoid membrane deterioration;

(c) Minimum Concentrate Flow Rate - it should be observed to avoid precipitation and consequent membrane fouling;

(d) Maximum Permeate Concentration - salt concentration in the permeate water is inversely proportional to the difference between the applied pressure and the osmotic pressure gradient across the membrane. If the applied pressure is less than a determined value, permeate concentration will exceed the limit of palatability of potable water (up to 1.0 kg/m3 may be considered acceptable, as suggested by the World Health Organization).

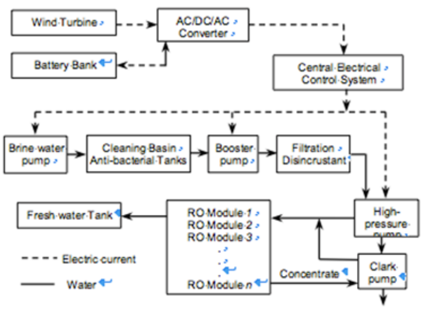

Figure 3: The wind-water desalination system

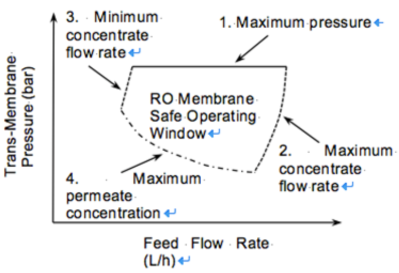

Figure 4: Safe operating window for a RO membrane as proposed by Feron (1985)

To demonstrate the use of the safe operating window, the performance of the wind-RO membrane system was optimised using the existing operating strategy, defined as constant set-point operation. The membrane system operates along one of the set-point lines shown in the safe operating window according to the available power and the position of the regulating valve on the concentrate stream, which is set at the start of operation. An integration and control unit is needed to manage power input to the water treatment system and the water treatment system must be properly managed. Several potential operating modes are available. The full functional representation of wind-RO membrane desalination system is illustrated in Figure.5.
The system has two subsystems: wind power subsystem and water desalination subsystem. With the potential operating modes defined, the choice of the optimal strategy should satisfy the following criteria: (i) allow the membrane system to operate within the safe operating window; (ii) optimise the performance in terms of the maximum possible flux and retention at low SEC (SEC – specific energy consumption (kWh/m3)); (iii) operate over a wide power range to utilise the power output from the wind turbine efficiently; and (iv) be robust, cheap and simple to implement. Due to space limitations, we describe the operating modes and their services briefly. “Full power supply” and “Allowable power supply” are two operating modes of wind power subsystem. “Wind turbine power supply”, “Battery bank power supply” and “Charging battery bank” are the services of these two operating modes. Similarly, the right of Figure.5 defines the related operating modes and services. This functional representation can describe the whole and complex wind-water desalination control system.

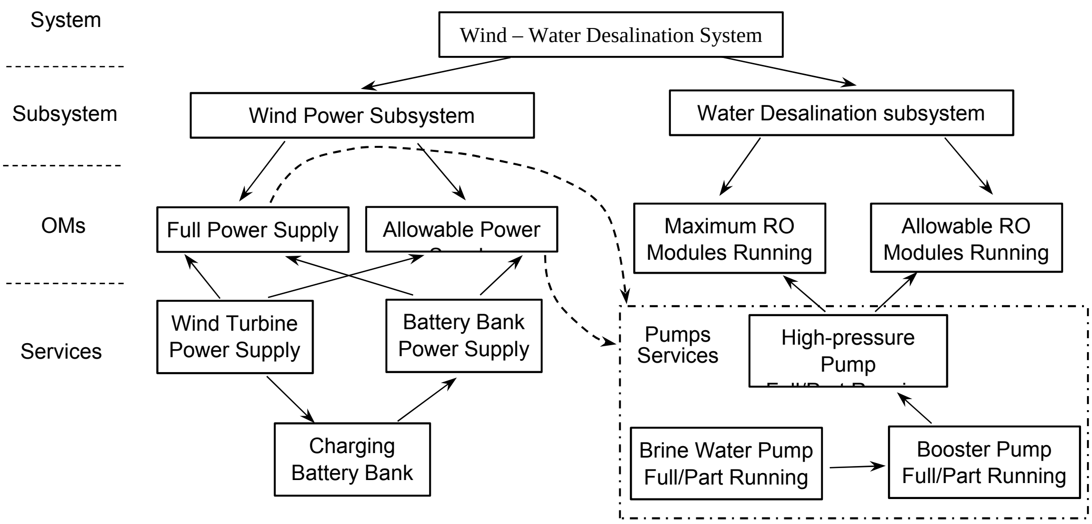

Figure 5: The functional representation of integrated wind-water desalination control system

5. Conclusions

In this paper, a model aggregation procedure based on generic component model has been proposed. Two elementary notions, the service and the operating mode have been introduced to construct a hierarchical system and to assure the coherences between realization possibilities and given specifications not only at each level of the system decomposition but also between the levels of the decomposition. It is a mean to expose the relation of “what the aggregated system could do” and “what it should do”. The important benefit of this procedure is that we can describe a system at any hierarchical level in a systematic way. Moreover it provides a unified framework for facilitating the knowledge acquisition of modelling. We illustrate our theory by an integrated wind-water desalination control system. To our future studies, we will develop the detail algorithm of this control system.

Acknowledgments

This work is supported by the Natural Science Foundation of Tibet Autonomous Region (Grant No.2015ZR2013-38) and the Fundamental Research Funds for the Central Universities of China (Grant No. 2011B09414, 2012B03614).

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