Bond Graphs as Mechatronic Approach for Supervision Design of Multisource Renewable Energy System

Belkacem OULD BOUAMAMA, Ibrahim ABDALAH, Anne-Lise GEHIN

Lille University, CRIStAL, UMR 9189, 59650 Villeneuve d'Ascq, France

Belkacem.ouldbouamama@polytech-lille.fr

Abstract. This paper deals with the bond graph methodology as a decision-making tool and multiphysic approach for supervision supervision system design. The developed algorithms have been applied to a mechatronic represented by Hybrid Renewable Energy System (HRES) which consists of Solar Photovoltaic Panels (PV) and wind turbines coupled to an electrolyser for hydrogen production used an energy vector for a fuel cell.

1. Introduction

Supervision is a set of tools and methods allowing the control of industrial processes in normal working as well as in presence of failures. At FDI (Fault Detection and Isolation) and FTC (Fault Tolerant Control) levels of the supervision and in the case of incidental or accidental situations, two kinds of information have to be displayed to operators. The first one concerns the detection and isolation of the fault, and the second deals with the way of continuing to control the process (reconfigurability). In order to help operators in those tasks, the integration of decision-making tools in the supervision system is needed. On one hand, supervision is associated with alarm processing to insure the safety based on dynamic model for fault indicators generation for online FDI. On the other hand the from human point of view, supervision system is seen by the operators in terms of functions and services (or missions) to be achieved. The set of services is organised into coherent subsets, called a User Operating Mode (USOM). At each time, and according to the technical specifications, a system carries on a coherent subset of missions. Each of these subsets is called operating mode. The supervision platform can be seen thus as a finite automaton $G(A,\tau)$ where A is a nodes representing a set of services and τ is the Boolean transition from one node to another controlled by the FDI system: a hardware failure (provided by FDI layer) implies the unavailability of some services and could put back the pursuit of some missions in question [1].

This paper deals with the BG methodology [2] as a decision-making tool for supervision plateform design. The BG as a unified, multi disciplinary and understandable approach is well adapted for those tasks. Indeed, in the normal situation the BG model shows clearly to the operator the physical phenomenon and the power flowing in the process [3]. Furthermore, in incidental or accidental situations, the causal properties of the bond graph allow the operator to resolve problems related with the safety of the supervised process. Compared with classical approaches [4] such as the hybrid automata, the Operating Mode Management (OMM) is much effective due to the separation between the continuous dynamics, represented by the BG continuous state, and the discrete state governed by a classical automaton.

The paper is organised as follows: The first part of the paper presentsBG as integrated design for not only dynamic modelling but also for supervision systems in terms of FDI. The second part concerns the real application of developed methodology to a complex HRES applied to a Hybrid Renewable

Energy Systems (HRES) which consists of Solar Photovoltaic Panels (PV) and wind turbines coupled to an electrolyser for hydrogen production used an energy vector for a fuel cell. and the third section concludes the paper.

2. Bond Graph as integrated design for supervision systems

2.1. Bond graph theory for modelling and diagnosis

Complex mechatronic systems are considered as a combination of different energy components which are exchanging several powers. A BG which is a graph, G(S;A) is a unified graphical language for multi-physic domains. The nodes S represent physical components, subsystems, and other basic elements called junctions. While the edges A, called power bonds represent the power exchanged between nodes. This power is labelled by two conjugated power variables, named effort (e) and flow (f). The set of components named BG element is: $S = \{R \cup C \cup I \cup TF \cup GY \cup Se \cup Sf \cup De \cup Df \cup J\}$ The R-element represents a passive energy dissipation phenomenon, while C, and I model the passive energy storage elements. (Se), and (Sf) are the sources of effort and flow, respectively. Sensors are represented by flow (Df), and effort (De) detectors. Finally, J, is used to connect the elements having the same effort (1-junction), or flow (0-junction). The conservative energy laws are obtained from the latter. TF, and GY are used to represent transformers and gyrators, respectively. From the BG model state space equations can be automatically generated, dedicated softwares are used for it. As shown in Figure 1(a), the power exchanged between two systems A and B indicated by a bond is the product of two variables - a potential variable (e.g. pressure, electrical potential, temperature, chemical potential, force, etc.) called effort (e) and a current variable (e.g. volume flow, current, entropy flow, velocity, molar flow, etc.) referred to as flow (f). One important structural property of the bond graph is its causality concept (algorithmic level of modelling). In the BG, it is denoted by the cross-stroke on the right indicating that the effort acts to the right, the side of the cross-stroke while the flow is in the reverse direction. As example in Figure 1(a), assigned causality means that system A imposes efforts on B. In the corresponding block diagram given by the Figure 1(b), the direction of action is indicated by an arrow on each connection as illustrated. Independently of the causality, the direction of the positive power is indicated by the half-arrow on the bond.

Figure 1. Causal Bond Graph representation (a) and corresponding bloc diagram (b).

Bond Graph modelling technique has been extensively used owing to the behavioural, structural and causal properties, that provide a systematic approach towards development of supervision and fault detection and Isolation (FDI) of highly non-linear and complex thermo-chemical systems. In BG framework, the model based FDI is mainly based upon ARRs as developed in [2].

3. *Application*

3.1. Description of the process

The proposed approach is applied to model a small size experimental HRES presented in Fig. 9b. The system main objective is to produce hydrogen. The system is composed of two sources Photovoltaic Panel (PV) and Wind Turbine (WT) connected through a common DC bus to a battery, an Electrolyzer (EL) and a Proton Exchange Membrane Fuel Cell (FC).
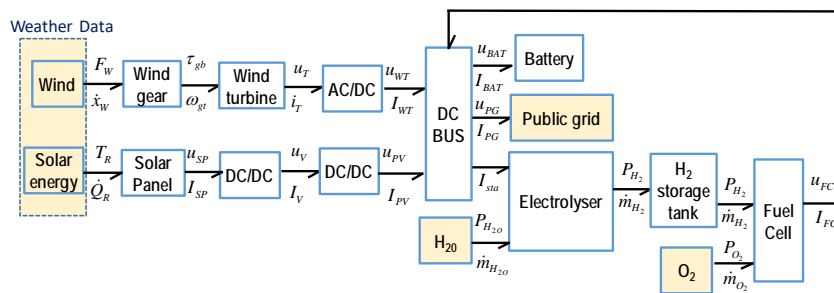
3.2. Bond Graph modelling

3.2.1. Word Bond Graph model (WBG). The technological level is represented by the word bond graph (Figure 3) which consists of decomposing the global system into subsystems. Comparing with

classical bloc diagram, input and output of each subsystem are the exchanged power (not an information signal).
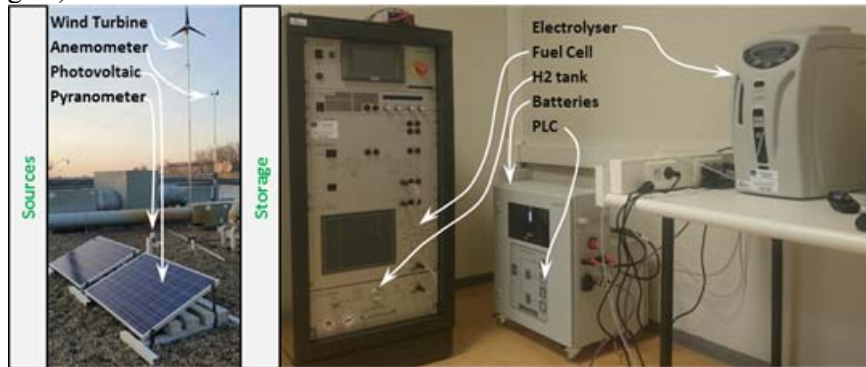
Figure 2. Overview of experimental multisource platform.

Figure 3. Word Bond Graph of the multisource platform.

3.2.2. Global bond graph model. The considered HRES is a real mechatronic system where occur not only electro mechanical energy but also chemical, thermofluidic, thermal and electrochemical phenomena. In the BG theory are used only a generic pair of power variables to represent all the phenomena. The used power variable (for pseudo and true bond graph) are the pair voltage-current (U, i) for electrical system, pressure-mass flow $(P, \dot{m})$ for hydraulic phenomena, temperature-enthalpy flow $(T, \dot{H})$ for thermal convection (Lagrangian point of view), temperature-thermal flow $(T, \dot{Q})$ for thermal conduction (Eulerian point of view), chemical potential-molar flow $(\mu, \dot{n})$ for chemical reaction and the pair chemical affinity-speed reaction (J, A) for chemical and electrochemical reaction. The global BG model is given Figure 4.

3.3. Supervision design of the system

As discussed before, the supervision platform can be seen as an automaton representing an operating modes management. Three operating modes are distinguished (Figure 5) *OM*1**: Low power** This mode is accessed when the power generated by the renewable sources does not cover the demand. In this case, the batteries are drained at first and then eventually the FC is triggered to use the stored hydrogen as a power back-up and prevent the power shortage. *OM*2**: High power** This mode is activated when the power generated by the renewable sources overcomes the required load. The power surplus is then stored as hydrogen using the Electrolyzer or/and as electricity using the batteries. *OM*3**: Safe power** This mode is activated when the system fails to provide the required power or when one or more faults occur which make some critical components to be unavailable. The availability of the hardware resources, used in each version, for each mission and then for each mode are evaluated by FDI system to control the transition signal τ_{ij} from the mode i to the mode j.

3.4. Simulation and Experimental results

The global system has been simulated using dedicated software ©20sim. Two scenario have been considered. Scenario 1 concerns the normal faultless behavior of the system represented by Figure 6.

The simulation uses 24 hours weather data of a sunny, average winds day1. The batteries are initially charged at 32% and the hydrogen pressure is about 93% of the maximum capacity of the tank. Between t=[00:00h] and t=[11:45h], the sum of both wind and the solar powers P_r were more than enough to satisfy the load $P_r > 200W$. The system starts then in OM_2: High power. The surplus is stored as hydrogen and electricity using both the electrolyzer and the battery. Between t=[11:45]h and t=[13:02]h, the generated power of the sources drops but still more than the load demand $100W < Pr < 200W$. The system still operating in OM2, the activation condition of the electrolyzer is then satisfied, as a result, the EL is deactivated and only the batteries are used to store power. After t=[13:02]h, the generated power of the sources drops to less than load required power $Pr < 100W$. As a consequence, the system switches to low power mode $OM1$.
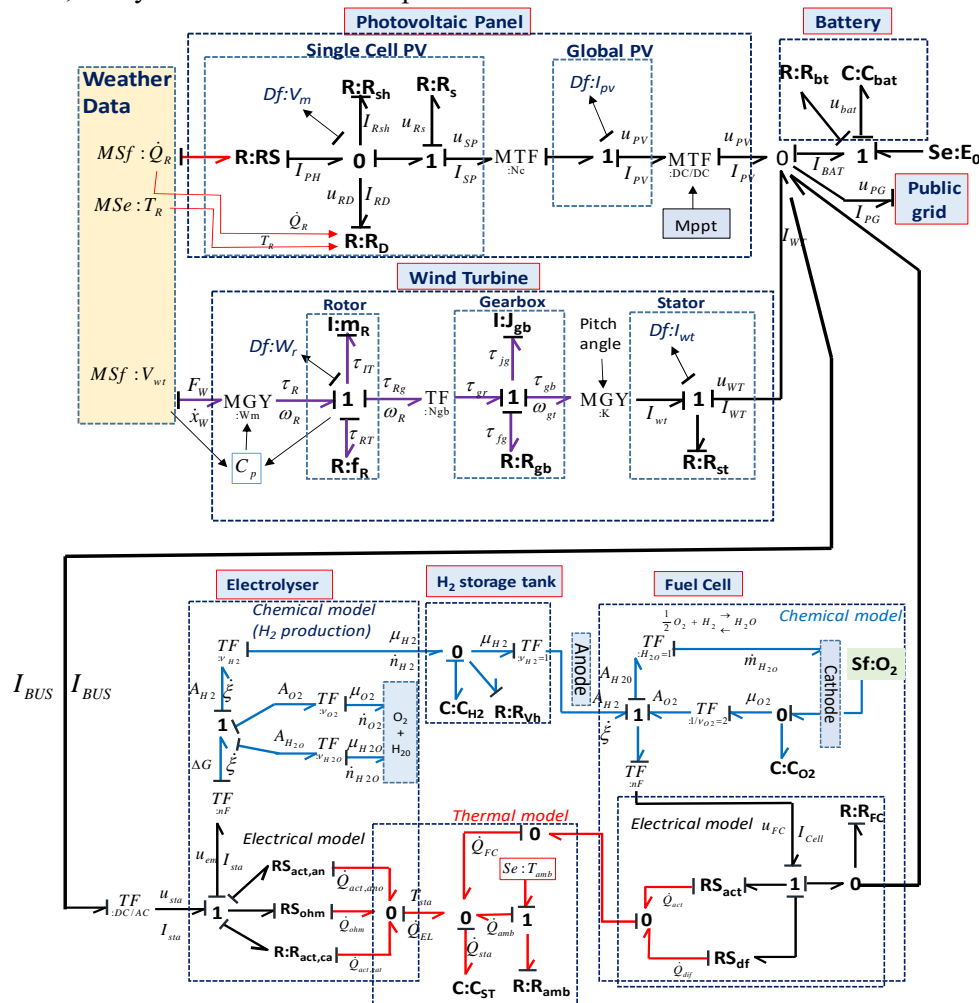

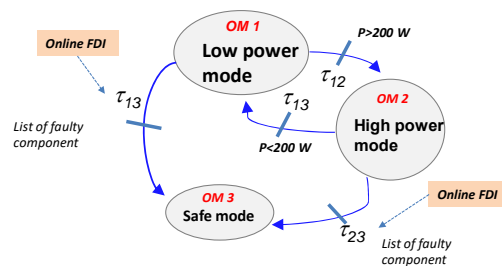**Figure 4**. Bond Graph of the multisource platform

Figure 5. Operating Mode Management supervision.

Scenario 2: Leak in the Hydrogen tank. We consider a leak in the hydrogen tank between t=[10:30-12:30]h. The system, as before, starts in *OM*2, residual signal sensitive to this fault (Figure 7a) overpasses the thresholds indicating the leak detection. When the detection occurs at t=[10:30]h the hydrogen tank is marked as unavailable, consequently the unique version of the mission: secure the H_2 become unavailable. Consequently, *OM*1 and *OM*2 become inaccessible. According to the OMM, the system must switch to the safe mode *OM*3 (Boolean variable τ_{23} or τ_{13} controlled by online FDI becomes 1) when the H_2 leak occurs, fault has been detected and isolated, both sources (wind and solar) are stopped, and their output powers are zero (Figure 6). The Figure 7b illustrates the generated and consumed powers of FC and EL. It shows that the EL is also shut-down after the detection, while the FC is activated in order to reduce the H_2 pressure.
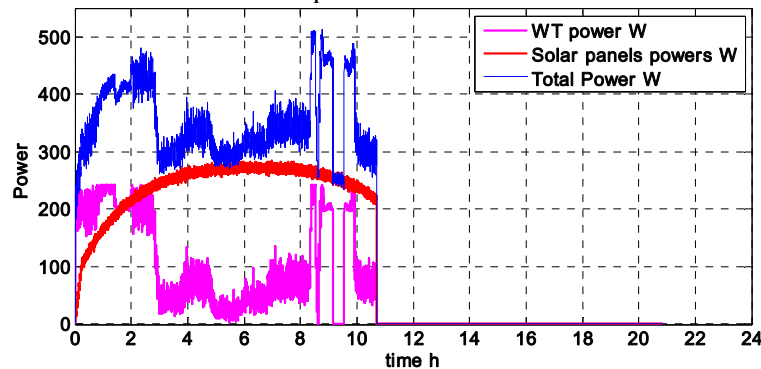

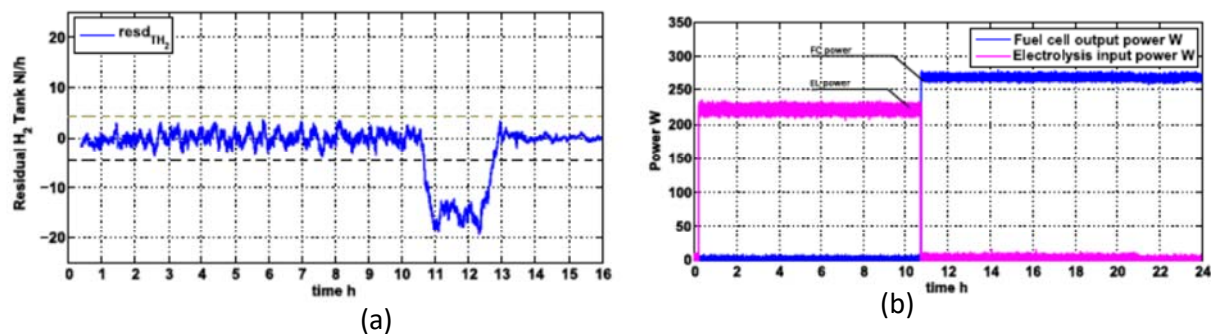**Figure 6**. . Simulated generated power.

Figure 7. Residual signal reaction to the H_2 tank leak (a) and corresponding FC and EL powers (b) .

4. Conclusion

A Hybrid Renewable Energy System is a complex mechatronic system because of coupling of several kind of energies. Optimal operating mode management of such process need an unified language for modelling and supervision in terms of safety and control. For those tasks it is shown how the Bond Graph as an unified methodology and a real integrated tool is used not only for modelling but also for supervision design. The developed methodology is applied here online to a real multisource platform.

References

[1] Ibrahim, A.L. Gehin and B. Ould Bouamama , *Event Driven Hybrid Bond Graph for Hybrid Renewable Energy System,* Part I: Modelling and Operating Mode Management. International journal of hydrogen energy, DOI: 10.1016/j.ijhydene.2017.10.144 , December 2017

[2] Ould Bouamama, B. *et al*. *FDI of Smart actuators using Bond Graphs and external models.* Control Engineering Practice, vol. 13, n°2, pp. 159-175, 2005

[3] A.K. Samantaray and B. Ould Bouamama. *Model-based Process Supervision. A Bond Graph Approach*. Springer Verlag,, 490 p. ISBN: 978-1-84800-158-9, Berlin, 2008

[4] B. Ould Bouamama, *et al* "*Graphical methods for diagnosis of dynamic systems:* Review" Annual Review in Control doi:10.1016/j.arcontrol.2014.09.004, Vol. 38, Issue 2, 2014, pp. 199–219.