A View on Advanced Standby Control in Industry from a Knowledge Engineering Perspective

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Keywords: Energy Efficiency, Energy Management, Standby Control, Knowledge Acquisition, Knowledge Engineering, Energy Engineering.

Abstract: In improving the energy efficiency of industrial plants, advanced standby control depicts a strategic instrument subject to various influences and with impacts on models and software tools along the entire plant lifecycle. In order to effectively switch plants and components to different levels of energy consumption, the required knowledge needs to be properly engineered and applied. This paper presents an overview of this knowledge and its interrelations in the industrial domain, with special focus on the requirements for automated generation of energy state models and switching paths. For these tasks, integrative approaches are proposed.

1 INTRODUCTION

Reducing energy-related expenses without negative effects on productivity is a prime goal in many manufacturing industries. Yet, these expenses are often a result of the way plants are operated: Machinery is kept ready for production, even during non-productive phases (Hübner, 2011). In such cases, situatively switching components to a lower energy consumption state and back to production state offers a large savings potential. This is a facet of "intelligent plant control tailored to situative needs", which has been identified as the technical trend with both the highest potential for making improvements in the field of energy efficiency and the highest need for R&D (Bründl et al., 2015).

However, in terms of the energy transition, as promoted by the German government (BMWi, 2014), the importance of this goal will likely decrease as decentralized power generation and storage is increasingly emphasized. Thus, the currently primary advantage of standby control (SC) will lose in importance in favor of other motivators for standby. First, the concept of "carbon footprint" is a main value in the energy balance of various industries (IEA, 2007). Further, components are subject to wear. Standby phases might affect underlying processes, and timely powering down a component might therefore help prolong its lifetime. In coupling SC to indicator values, and in cases where the course of wear is actively influenceable, standby is another tool in predictive maintenance (Mobley, 2002). Another potential use comes from standby as a redundancy concept in interplay with energy consumption. This addresses component availability while simultaneously reducing costs, which is the object of reliability-centered maintenance (Moubray, 1997). For this, parameters like maintenance schedules are needed.

An advanced SC system is vital for the pursuit of such motivators. This requires a consistent and integrated model of the domain and plant, together with representations of standby strategies to be employed, linked to manufacturing execution systems and asset management systems. In light of the demands for integrated plant IT systems (Sauer, 2010), SC systems will eventually become an integrated functionality. Based on existing technologies of SC, we propose a basic approach that permits the generic integration and combination of standby-related knowledge to dynamically generate switching sequences and thus flexibly apply standby strategies.

This paper is organized as follows: Section 2 lists work related to this topic. Section 3 describes exemplary SC technologies. Section 4 highlights the knowledge necessary to operate SC, and Section 5 presents the basic approach. Section 6 concludes the paper.

Mueller, A. and Peschke, J..
A View on Advanced Standby Control in Industry from a Knowledge Engineering Perspective.
In *Proceedings of the 7th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management (IC3K 2015) - Volume 2: KEOD*, pages 364-369
ISBN: 978-989-758-158-8

2 RELATED WORK

Schöfberger et al. (2010) point out the variety of aspects involved in SC in industrial production plants, such as equipment types, interdependencies among components as well as between components and processes, in order to describe and evaluate energy consumption. Along with transparency for energy-related data, standardized tools and plant models are therefore prerequisites.

Wolff et al. (2013) elaborate on the requirements for the engineering of such SC systems, showing the demand for digital models and integrated toolchains. Emphasis is placed on the distinction between static information models for intrinsic properties of the plant and models for dynamic behavioral aspects.

Focused on the domain of machine tools, the research group ECOMATION presents an approach to the description and exchange of energy-related knowledge using a special Energy Information Description Language (EIDL) (Schlechtendahl et al., 2013). Here, consumers in machine tools and their interplay are described by interrelated models and linked to the underlying physical components.

3 STANDBY CONTROL TECHNOLOGIES IN INDUSTRY

3.1 Basic Terminology

The term “standby” actually subsumes several energy-saving modes, distinguished by their levels of energy consumption. Böde et al. (2000) name four basic modes. In *normal mode*, a device fulfills its main task at a level of 100%, while in *general standby mode* it does not fulfill its main task but can be reactivated at any time. This mode can be subdivided into the *ready(-to-use) mode* with almost no decrease in consumption, the actual *standby mode* with reduced consumption, and *sleep mode* with the largest decrease in consumption. Another mode is the *pseudo off mode*, in which a device still absorbs energy despite being switched off physically (an error state). The last basic mode is the actual *off*, with no power consumption at all. In this paper, these modes will also be referred to as *energy states* ε. Finally, various *triggers* exist for activating a standby mode. These may be device-specific, time-based presets as well as external schedules, e.g. pause schedules or reactions to unplanned situations such as faults.

3.2 Technologies

Initiated by the German automotive industry, **PROFIenergy** (PE) aims to reduce power consumption of production plants through controlled switching to standby mode during non-productive phases, based on the PROFINET field bus (PNO, 2010). PE serves the four use cases *brief pauses*, *longer pauses unscheduled pauses*, and *measuring and load visualization*. Any device supporting PE needs to individually implement the responses to the mandatory commands. The architecture is based on one PE controller acting as managing instance for many PE devices representing the components to be controlled. Here, time – as requested durations for pauses – is the only criterion: The controller receives a standby request for a specific duration (e.g. pause for 15 minutes), and sends *Start_Pause* and *End_Pause* commands to devices in a timely manner. The devices then autonomously determine the ε they can switch to, while guaranteeing the return to production mode when needed. For this, a state model with mandatory and optional transitions between states is employed (Figure 1). This covers a spectrum of discrete ε ordered by their associated consumption levels and the length of time required to return to production mode.

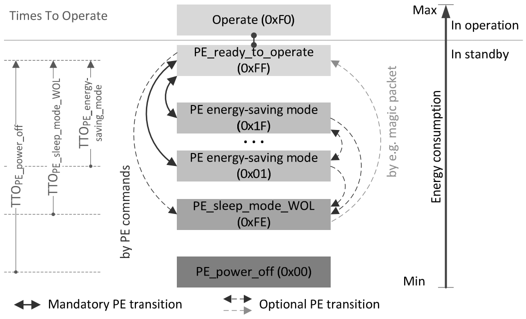

Figure 1: PE state model (adapted from (PNO, 2013)).

Sercos Energy (sE) is an application profile for the sercos field bus system common in the domain of production machines (Schlechtendahl, 2012). In addition to the also-covered PE use cases, two scenarios are served: *partial machine operation* (switching off temporarily unneeded components) and *partial load operation* (adapting the machine’s energy consumption according to production completion dates). The architecture is also 1:n-based with a controller and subordinate devices. A sercos controller is called *coordinating system*, as it is aware of the overall process state and its influences on the devices, permitting standalone device control. Underlying this functionality is a rich state model with discrete, semantically divisible ε and with mandatory and optional transitions (Figure 2) (sercos, 2011). Unlike PE, the sE state model permits three mixable modes of control: ε may be directly addressed, durations for pauses may be provided (“PE mode”), or a maximum level of energy consumption may be specified. Switching to off mode is hence permitted.

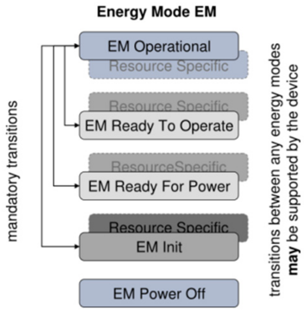

Figure 2: sercos Energy state model (from (sercos, 2011)).

The **Energy State Controller** (ESC) is a result of a work conducted at a Siemens research facility for manufacturing automation. Built upon existing technologies for communication and plant control, it can perform fine-grained switching of production plants and subsystems to predefined ε. The ESC employs an automaton-based approach that requires a predefined plant model covering aggregation hierarchy, state models per component, conditions and costs for switching, and qualification of transitions by temporal constraints and states of subordinate components as preconditions. Details are given in (Mechs, 2013). The architecture comprises 1 controller and n devices, operating on individually addressable state machines. Calls to devices are coordinated by the controller, based on current subordinate ε and process values. Unlike PE and sE, the ESC permits arbitrary topologies of states to be defined. Target ε or durations for pauses can be stipulated, and the required ε for each component are inferred from these. For this, the sequences for reaching any state are inferred from a static model.

4 KNOWLEDGE ENGINEERING

Today, the desired behavior for such SC needs to be manually programmed or modeled, with the key challenge of properly determining, applying, and monitoring the switching actions in reaction to triggers. These steps are complex and error-prone. This section provides an overview of the relevant knowledge to be engineered in order to enhance generic integration in plant software systems.

4.1 Switching Paths

Due to interdependencies between components, switching actions need to be performed in specific sequences. This ordered set of actions, which is later executed by a dedicated logic, is subsequently referred to as the *switching path* σ, with three basic phases and corresponding knowledge entities. First, *before switching*, the dependencies and valid actions need to be determined in order to generate a basic σ. This needs to be checked for both prospective duration and effects being in line with the specific demands of the desired action, and whether returning to the productive state can be guaranteed. Second, if the σ is executable, it is mandatory to verify *on the path* that the next pending switching action can be performed and, after this, whether the action has been traceably completed according to the expected effects. Third, *after switching*, it must be checked that all affected components now inhibit the target ε as expected. Consequently, two main qualities are essential for any handling of a σ: Systematic knowledge management is required to provide the plant knowledge and suitable diagnostics must be present to interpret actions’ results and to identify and initiate remedial measures.

4.2 Categories to Be Covered

The knowledge required for handling ε may be subdivided into four categories. First, there is *structure and functionality*, i.e. the static and dynamic aspects of the plant. Covering components, their interdependencies, processes and their effects, this depicts the basic knowledge for determination of σ. The second category classifies components by their *switchability*: *Non-switchable* or *always on* components (e.g. safety controllers) as well as those *non-switchable by programmable logic controllers (PLC)*(e.g. lighting systems) do not contribute to energy efficiency through SC, whereas those *switchable on-demand by PLC* (e.g. conveying systems) are the most relevant for SC as they are switchable in dependency on a process or PLC program. The third category covers the *effects of actions*. This subsumes knowledge on components being affected and on the delays the actions’ effects usually require to become apparent. Finally, the fourth category handles *classifications of the components’ states according to the energy* *consumption levels*. This addresses the ε-specific energy consumptions as well as the energy demand for transitions between ε.

4.3 Diagnostics

Effective diagnostics of SC requires a cross-level view. While determination of σ and coordination of their execution takes place on a plant or subsystem level, switching actions are performed on the field level with typically heterogeneous devices. Requests for switching actions run from control level to field level over various communication technologies and field bus systems. As failures and effects may generally involve all levels in arbitrary combinations, full diagnostics must cope with this issue. The knowledge described above forms the basis for this. However, this basis is highly dynamic: First, the plant itself is subject to change during its lifecycle and second, all related knowledge is subject to refinement (Figure 3; arrows symbolize different communication technologies).

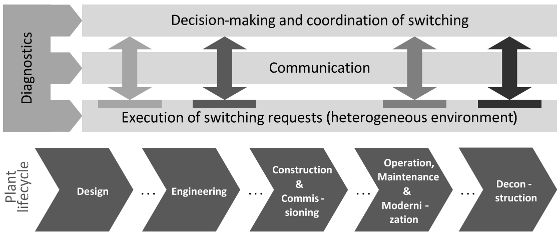

Figure 3: Interrelations of knowledge.

A special challenge arises from the infrastructure connecting the levels, as different technologies with own diagnostic functionalities are employed, e.g. (PNO, 2015) or (IO-Link Community, 2013). Thus, a great deal of knowledge needs to be captured redundantly, due to incompatibilities. Hence, an overall approach for diagnostics is strongly advised.

4.4 Towards an Integrated Standby Management

In terms of the topics presented above, the following basic methodology for knowledge organization is proposed for creating an integrated SC system (Figure 4). A concept for knowledge distribution must be established initially. Strategies must be adopted for handling the knowledge needed for generation of σ and for coordinating its execution, and to provide all involved components with the necessary information. On this basis, domain models that describe the plant in terms of structure and function are introduced. This references aspects of knowledge distribution as these mechanisms are part of the plant. Energy state models are developed, based on this. These describe the ε of the components and processes, along with their interconnections. An idea for this is given in (Schlechtendahl et al., 2012). Next, switching strategies are defined. As switching actions are transmitted over communication channels and affect components and processes, this information needs to be available in order to evaluate the plausibility of a strategy (see (Wolff et al., 2013)). Finally, models for diagnostics are created. These contain knowledge about the interpretation of phenomena observed during switching actions.

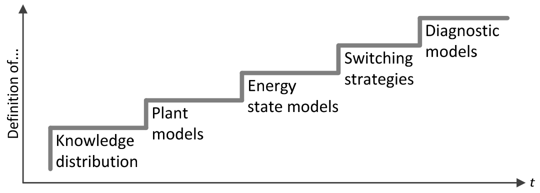

Figure 4: Knowledge organization methodology.

5 A UNIFIED SWITCHING MODEL

Having presented the knowledge relevant for SC, we will now outline an integrative approach to the generation and application of energy state models.

5.1 Switching Matrix

Switching to an ε is bound to certain preconditions and has certain effects. In addition, the criterion for switching may either be duration, a target ε, an associated attribute, or a combination of these along a σ. Based on their characteristics and by interpreting state models on the graph level, we propose the organizational means of a *switching matrix M* as the central generic knowledge structure for handling energy state models.

$$M := \begin{pmatrix} 0 & S_0 & S_1 & \cdots & S_n \\ S_0^{-1} & 0 & T_{S_0,\,S_1} & \cdots & T_{S_0,\,S_n} \\ S_1^{-1} & T_{S_1,\,S_0} & 0 & \cdots & T_{S_1,\,S_n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ S_n^{-1} & T_{S_n,\,S_0} & T_{S_n,\,S_1} & \cdots & 0 \end{pmatrix} \tag{1}$$

Built upon the adjacency matrix of the respective state graph, *M* has the following properties:

- A header row and column is added, with distinct elements for entering and leaving (“$^{-1}$”) states *S*, linked by transitions *T*. The order of the *S* within *M* reflects the levels of energy consumption, with S_0 for normal mode (operational state) and S_n for maximum energy-saving mode (lowest standby).
- Each element is defined as an individual criterion-based (*c*) evaluable configuration *f*(*S, c*), *f*(*T, c*) of preconditions *P* (must hold for the *S*, *T* to be considered), actions *A* (performed upon valid *P*), and effects *E* (occur by performing the *A*): $S, T := \langle P, A, E\rangle$. An *S* may comprise distinct ⟨*P*, *A*, *E*⟩ for entry/exit. An *E* may comprise both triggering of switching actions and changes of values. The criterion and thus evaluation result may be duration, state, or attribute value.
- All *P*, *A*, *E* are rooted in the underlying plant models through their elements referencing plant entities with evaluable and modifiable attributes.
- Missing or prohibited *T* as well as elements along the main diagonal evaluate to neutral.

The potential states for each component can be inferred from the energy-consumption properties and the components' interrelations in the plant model. Ultimately, a σ depicts a trajectory in this search space, whose determination is controlled using policies or switching strategies, which effectively depicts a planning problem. Hence, different modes of control can be realized by means of *M*. E.g., since PE mode requires finding the lowest ε possible for a given t_{Pause}, starting at a current state *x*, this can be modeled using (*c* as duration omitted for brevity):

$$\begin{aligned} & f(S_x)+f(S_x^{-1})+ \\ & \sum_{i=x+1}^{n}\Big(f(T_{i-1,i})+f(S_i)+f(S_i^{-1})+f(T_{i,i-1})\Big) \qquad (2) \\ & \le t_{Pause} \end{aligned}$$

Switching matrices may be employed at any level of a plant, with ideally one *M* per component. Viewing an *M* as a container for inferred knowledge, they may be centrally engineered on the manufacturing execution system level and deployed to both controller and device level, along with the logic for σ generation. In addition, when initially supplied for lowest (field) level components, higher-level *M* may be inferred bottom-up.

5.2 Automated Generation of Switching Matrices and Paths

Switching paths depict sequences of actions on a dynamic knowledge corpus. Also, the domain of SC is well-defined in terms of relevant relationships. By taking advantage of these facts, dynamic taskflow generation (Brecher et al., 2010) can be used for the automated generation and population of *M* and for the generation of σ. There, *A* are defined by ontology-based *P* and *E* inferred via rule sets. Given a state-based task on a plant model as parameter, the proper sequence of *A* is inferred via a state-based planning approach. This utilization is outlined in the following.

M act as guides to each component's energy states and thus to the *A* required for switching ε. Hence, determining these *A* is a prerequisite. For this, the following information is required:

- Meta-model-based rules for prioritized handling of components according to the basic semantic relations of *is-part-of*, *is-a*, *is-related-to* as well as *depends-on*, and according to the roles they occupy within the relationships: For entries/exits of *S*, additional semantics can be defined. Prioritizations can be specified either by precedence or by temporal relationship (Allen, 1983), e.g. ∀*x*, *y*: *depends-on* (*x*, *y*) → *after* (*x*, *y*). This was impractical for the maintenance and service domain of the original approach, due to the great variety of relations. Yet, this is feasible for the domain of SC as the set of distinct relations is much smaller.
- The characterizing relationships between components in the plant model: In combination, these specify candidate classes for *P*.
- The overall *E* to be achieved on the classes given by the *M*, along with the information about the component values that need to be set to cause the *E* and whether activation is permitted.
- The initial state of the model.

While iterating over an *M*, the ⟨*P*, *A*, *E*⟩ are inferred for each element, with initial *P* of the target state not being met. The candidate classes are determined by finding those components for which any of the given rules would fire. In conjunction with this, the premises of those rules identified as valid for candidates constitute the *P* that are required to hold for an *A* to be performed while the *E* are defined as the states to be reached. With the actions at hand, the required σ can be inferred. For this, a reverse search strategy is applied on the search space given by the plant model and the associated state space. Starting with the one *E* representing the target state on a considered component, the associated *P* are matched with other *E* that cause the respective *P* to hold. This search yields a raw σ, typically with multiple relevant *P* and *A* required for an *E*. Using the prioritization rules, this graph is linearized in analogous reverse search manner, yielding the final σ. This reasoning process can either be applied a-priori in order to provide and deploy fully qualified M or it can be performed on-demand. Hence, dynamics of the plant model can be met appropriately. In conjunction with diagnostics, this also permits the automatic generation of bypass solutions for σ. In addition, other scenarios based on sequences of actions can be handled with this approach as well.

6 CONCLUSION AND OUTLOOK

Although it appears to be a simple task at first glance, a thorough examination of "standby" in an industrial context requires broader consideration beyond the original focus on energy efficiency. Switching industrial plants to energy states during non-productive times requires that consideration of many details that extend into different adjacent domains. This requires systematic and integrated knowledge management that combines disparate knowledge artefacts across the entire plant lifecycle.

This paper has highlighted aspects of knowledge engineering significant for the enabling of comprehensive advanced standby control (SC). In addition, it presented an approach to the flexible, automated provision of the necessary energy state models and switching paths. Future work will address the evolution of the tools and components involved in plant automation, with the goal of offering advanced SC as an integrated feature. Also, in light of the evolving general frameworks, the implications of advanced SC as a dedicated tool must be evaluated in the contexts of predictive maintenance and reliability-centered maintenance so that its potential can be classified.

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