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Industrial energy systems in view of energy efficiency and operation control

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ABSTRACT

Energy efficiency improvement of industrial systems through the application of demand side management (DSM) techniques is discussed. In particular, a unified classification of efficiency of energy systems, namely performance efficiency, operation efficiency, equipment efficiency and technology efficiency (POET), is reviewed and further discussed to facilitate effective use of DSM methods in a selection of energy-intensive industrial processes. The operational level efficiency improvement is then focused on and the corresponding modelling and control by model predictive control (MPC) approach are presented. The modelling process is generalised to cater for a number of industrial processes. Robustness and convergence of MPC method when applied to periodic industrial processes are elaborated. The relationship between control and the POET is outlined thereafter to link the two such that one can make use of the POET concept to guide the controller design. Finally, case studies are provided to demonstrate the effectiveness of the approaches presented.

1. Background

The world has been actively seeking for less energy-intensive and renewable technologies for decades to promote sustainable and environmentally friendly development. The energy challenges faced by the world since 1970s were the driving forces of energy-efficient operation of many energy consuming processes[1]. Although some argue that improving energy efficiency will lead to more affordable energy and its use, thus resulting in more consumption (Herring, 2006), the fact that energy efficiency improvement ensures less consumption per activity or production unit is of great value for a greener society.

Among other solutions, energy efficiency improvement through demand side management (DSM) technologies has shown its effectiveness in reducing energy usage in various applications. In particular, it is known that the industrial sector consumes about 37% of the worlds total delivered energy (Gellings, 1985), reducing consumption by this sector thus will make a big difference in terms of the world's energy scenario.

DSM programs seek to reduce the gap between power supply and demand broadly by conservation, load management, fuel substitution, load building and self-generation, among which energy conservation, commonly known as energy efficiency (EE), and load management (LM) are the most popularly used methods in the industrial sector (Abdelaziz, Saidur, & Mekhilef, 2011). The LM approach aims to reduce electricity demand at peak periods by means of monetary incentive to shift load to off-peak periods, e.g., in the form of a time-of-use (TOU) tariff or a demand response programme (Eissa, 2011; Saini, 2004). The EE approach aims to reduce overall electricity consumption by installing energy efficient equipment and/or optimising industrial processes.

Numerous application of DSM techniques to various industrial systems were reported in the literature. For instance, DSM technique was introduce to reduce energy consumption and the associated cost for industrial and domestic pumping systems (van Staden, Zhang, & Xia, 2011; Zhang, Xia, & Zhang, 2012, 2014; Zhuan & Xia, 2013a,b). The operation of heavy-trains was modelled (Chou, Xia, & Kayser, 2007) and controllers were designed to optimise the safe and energy-efficient operation of the trains (Chou & Xia, 2007; Xia & Zhang, 2011; Zhang & Zhuan, 2014a, 2015; Zhuan & Xia, 2006, 2007, 2008, 2010). Operation modelling and optimisation for hybrid solar power systems were studied in (Tazvinga, Xia, & Zhang, 2013; Tazvinga, Zhu, & Xia, 2014, 2015; Wu, Tazvinga, & Xia, 2015; Zhu, Tazvinga, & Xia, 2015). Applications of DSM technologies, including modelling, energy management and operation control, to mining processes, such as conveyor belts (Mathaba & Xia, 2015; Shen & Xia, 2014; Zhang & Xia, 2010; S. Zhang & Xia, 2011), rock winders (Badenhorst, Zhang, & Xia, 2011), crushers (Numbi & Xia, 2015, 2016; Numbi, Zhang, & Xia, 2014), ventilation systems

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[1] The History of Energy Efficiency. Alliance Commission on National Energy Efficiency Policy, 2013.

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(Chatterjee, Zhang, & Xia, 2015), coal washing processes (Meyer & Craig, 2010; Zhang & Xia, 2014; Zhang, Xia, & Zhang, 2015), etc., to save energy and cost were studied. In addition to applications to the demand side, similar techniques were also reported in the maintenance of power plants (Ekpenyong, Zhang, & Xia, 2012), and economic generation dispatching for power plants (Elaiw, Xia, & Shehata, 2012a; 2013; 2012b; Nwulu & Xia, 2015a,b; Xia & Elaiw, 2010; Xia, Zhang, & Elaiw, 2011). The list can be expanded extensively because of the abundance of such applications.

There is a need to present a general framework to guide the DSM activities for industrial systems to facilitate the identification of potential EE interventions by DSM techniques and to guarantee the effectiveness of the DSM measures employed. In this paper, a review of a unified classification of energy efficiency in energy systems to aid energy audit and EE measures design is presented. In addition, the optimal operation of industrial systems is discussed in detail from optimisation and model predictive control (MPC) perspectives.

Section 2 gives an overview of the unified energy efficiency classification in terms of performance efficiency, operation efficiency, equipment efficiency and technology efficiency (POET). Section 3 discusses the optimal operation of industrial processes. The relationship between POET and operation control is discussed in Section 4. Some case studies are provided in Section 5 to demonstrate the convenience and effectiveness of the application of the presented approach. Finally, Section 6 concludes this paper.

2. POET analysis of energy systems

Generally, DSM methodologies' application to industrial systems falls into the aforementioned two categories, namely EE and LM. In 2010, a unified classification of efficiencies in an energy system was proposed by the Centre of New Energy Systems at the University of Pretoria (Xia & Zhang, 2010b, 2011; Xia, Zhang, & Cass, 2012). This classification was then adopted by the South African National Hub for the Postgraduate Programmes to develop EE curricula and design national EE intervention policies and guidelines[2]. The introduced concept categorises efficiency of an energy system into four sub-efficiencies in terms of POET. The POET approach establishes an general framework to conduct energy audit, to identify energy saving potentials and to plan energy efficiency improvement interventions. A brief discussion of the POET framework is presented in the following sections.

2.1. POET components of energy efficiency

Technology efficiency is discussed first because technology dictates the possible efficiency rates in all other components.

Technology efficiency is a measure of efficiency of energy conversion, processing, transmission, and usage; and it is often limited by natural laws such as the energy conservation law. Technology efficiency is often evaluated by the following indicators: feasibility; life-cycle cost and return on investment; and coefficients in the conversing/processing/transmitting rate (Weston, 1992).

Technology efficiency is characterised by its novelty and optimality. On the one hand, ground breaking and feasible novel technologies often defeat older peer technologies and occupy the market quickly. On the other hand, these novel technologies always challenge optimality through the pursuit of scientific limits and the quest for possible extremes.

Equipment efficiency is a measure of the energy output of isolated individual energy equipment with respect to given technology design specifications. The equipment is usually considered being separated from the system and having little interactive effect to other equipment or system components. Equipment efficiency is evaluated by considering the following indicators: capacity; specifications and standards; constraints; and maintenance.

Equipment efficiency is specifically characterised by its standardisation and constant maintenance. The most important aim of equipment efficiency is to minimise the deviations of the actual equipment parameters to the given design specifications. The difference between equipment efficiency and technology efficiency is easily illustrated by considering the compact fluorescent lights (CFL) example: The study on the improvement of CFL technology to provide more efficient lighting facilities forms part of the category of technology efficiency improvement, while replacing incandescent lights with CFLs is part of the equipment efficiency improvement category.

Operation efficiency is a system wide measure evaluated by considering the proper coordination of different system components. This coordination of system components may consist of the physical, time, and human coordination parts. These parts can again be indicated by sizing, matching, skill levels, and time control of these system components. Operation efficiency has the following indicators: physical coordination indicators (sizing and matching); time coordination indicator (time control) (Middelberg, Zhang, & Xia, 2009); and human coordination. In particular, sizing of one system component is to consider the relationship of this component with respect to the rest components of the system, thus sizing of the system component is an operational issue comparing with the capacity consideration in the equipment efficiency context.

Performance efficiency of an energy system is a measure of energy efficiency which is determined by external but deterministic system indicators such as production, cost, energy sources, environmental impact and technical indicators amongst others. It is worth noting that sometimes these performance efficiency indicators are contradictory or in competition with each other. An energy system will be expected to maximise the production and at the same time minimise cost and emission. Therefore the performance efficiency can only be improved when certain trade-offs among different indicators are made. The sustainability of the energy system can be reached if the engineering indicators (e.g., sources, technical indicators) do not compete with those socio-economic indicators (e.g., production, cost, environmental concerns). Apart from the indicators listed above, all the performance, operation, equipment and technology efficiencies are affected by technical, human, and time factors. For example, human wisdom and the corresponding decisions are often deterministic to technology efficiency; and a time-of-use electricity tariff will stimulate the improvement of performance efficiency.

The four POET efficiency components may not have clear-cut boundaries, they may also exist at micro-level underneath a more visible macro-level, exhibiting a multi-layer structure.

2.2. Implications of POET

Technology efficiency is a deciding factor to equipment efficiency, operation efficiency, and performance efficiency (see Fig. 1). The deterministic relationships can be used to further decompose the POET components. In Fig. 1, equipment efficiency has two parts E1 and E2. E1 represents the differences between output energy and specification, while E2 denotes the efforts such as maintenance which can help the equipment to keep its specifications. E1 is directly affected by technology efficiency but E2 is not.

[2] Eskom Energy efficiency and Demand Side Management Program Evaluation Guideline Proposal–A POET Based Measurement and Verification Approach from the Engineering, Environmental, Social, and Economic Aspects, 2011.