Quantifying the Demand-Side Response Capability of Industrial Plants to Participate in Power System Frequency Control Schemes

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Abstract—Efficiency and sustainability considerations have propelled changes in power and process industries. These changes, which include the increased electrification of process industries, are causing concerns about the reliability of future electricity supplies, and therefore motivate the need for a Smart Grid on an industrial scale. This paper presents a method by which process automation engineers can assess the suitability of an oil and gas plant to participate in power system frequency control services. This paper discusses the necessary specifications for an automated system that enables effective variable operation by analysing the safe operating envelope of the plant. To do that, this paper proposes a methodology to characterise the appropriate actuators, variables and limits of set-point change. This methodology is applied to a case study representing an oil processing facility. The resulting analysis indicates demand-side response capability that the facility can provide without jeopardising operations on-site.

Index Terms—Demand-side response, Industrial Smart Grid, load capability, power system frequency control

I. INTRODUCTION

The process industries are having a growing impact on electrical supply. In oil, gas and petrochemicals, sustainability, efficiency and maintenance considerations are leading to electric motors taking over traditional gas turbine drivers for pumps and compressors. Steel-making and minerals industries use electric motors to power steel rolling and rock crushing equipment, while pulp and paper manufacture also requires extensive use of electric motors. Electricity is also used directly in electrolysis and smelting processes. Taken together with increased generation from renewable sources, increased electrification of the process industries motivates the need for a Smart Grid on an industrial scale (the Industrial Smart Grid) to improve security of supply [1].

Industrial processes depend heavily on a reliable and continuous supply of electricity. An unplanned shut down may result from a frequency deviation event leading to production and

Fig. 1. Types of DSR services specified by the European Network of Transmission System Operators for Electricity (ENTSO-E) [3]

monetary losses, compromised mechanical integrity of process equipment and safety concerns [2]. A shut down might, however, be avoided by implementing appropriate strategies to support electrical grid operations. Therefore there is a strong motivation for the process industries to explore the topic of demand-side response (DSR).

The Process Systems Engineering research community has been examining how the chemical process industry can do load shaping and load shifting. The electricity purchase decisions are solved as an optimization problem [4]- [5], and the decisions are implemented by participation in the day-ahead and intra-day energy markets. On the other hand, [6] have investigated and quantified industrial potential for automated demand side response service by providing Replacement Reserves. Replacement Reserve is a system frequency control function, as shown in Fig. 1. It falls in the category of automated DSR and is traded in the reserve power markets and balancing power markets. Other commentators are also starting to explore the possibilities of large industrial loads to participate in system frequency control [7]- [8]. The authors of [9] have shown that it is feasible for energy and power management systems already in use in large industrial sites to be adapted for the purpose of varying the electrical consumption of a site. They discussed the communications and automatic responses to request signals from the transmission systems operator (TSO) or an aggregator.

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Fig. 2. Block diagram of single area power system frequency control [12]

A question that is not yet being widely discussed, however, is how to assess the capability or suitability of an industrial site to provide a variable electrical response. This was recently addressed in [10] and [11] for metal smelting plants. This paper now presents a method by which process automation engineers can assess the suitability of an oil and gas plant to offer variable operation for system frequency control via the reserve power market.

The next section lays out the background information for this work. Section III outlines the proposed approach, while Section IV shows an example of its application and the results of the analysis. Section V demonstrates how the results can be used, and the conclusions are in Section VI.

II. BACKGROUND INFORMATION

A. Variable operation for system frequency control

Variable operation is a DSR strategy whereby process units temporarily change their operating set-points to vary their power consumption in response to a request signal.

Fig. 2 depicts the generic frequency control scheme for a power system [12]. It shows local and centralized controllers sending signals to providers of FCR (Frequency Containment Reserves), FRR (Frequency Restoration Reserves), and RR (Replacement Reserves). Traditionally, FCR units comprise of hydro power generators, with FRR and RR provided by thermal and nuclear power generators.

The motivation for the work presented in this paper is to enable industrial loads to provide FRR and RR, and to assess the capability of industrial plants to participate in system frequency control services by adopting variable operation.

Fig. 3 shows how an industrial plant can act as an FRR unit. The architecture presented is adopted from [4] and [13], in which the demand response logic is hosted by the plant's energy management system (EMS). Upon receiving signals from the grid, the EMS will dispatch signals (Δsp_i) in the form of a change in set-point or on/off signal to the *actuators*. In this case, actuators refer to process equipment such as pumps, compressors or electric heaters, which will provide the variation in power consumption (ΔP_i^m). The total change in power consumption ($\Delta P_{2,DSR}$) represents the provision of reserve capacity.

Due to the continuous nature of industrial processes, the inherent challenges in devising an effective variable operation strategy are to investigate which process variables are affected

Fig. 3. System architecture for an industrial plant participating in frequency control schemes as an FRR via variable operation

Fig. 4. Pressure protection system for an electric heater

by the set-point changes, how are they affected, and to what extent do these changes have an impact on the overall process. Process variables refer to flow rate, material composition, level, temperature, or pressure at any location in the process.

To address the above issues, this paper proposes a methodology to assess the capability for variable operation for an industrial plant by analysing the safe operating envelope of the plant. This envelope is characterised by the safety and protection system installed in the plant as explained in the next subsection, and the analysis is performed by means of process modelling.

B. Characteristics of industrial processes

Industrial plants host continuous flows of material and energy throughout the site. Therefore, any changes introduced to one part will propagate to distant parts of the plant. For example, reducing the speed of a pump will cause flow rates, levels and pressures to decrease in subsequent process units. These changes, if uncontrolled, can interfere with the safety and protection system in the plant, which then cause process trips leading to a plant-wide shut down.

Fig. 4 shows an example of the protection system for an electric heater HEX 101. This system is responsible for ensuring that the pressure inside the heater stays within the pre-set high and low pressure limits. Safety is provided by layers of protection systems [14]. For this paper, only the process control system and safety instrumented system layers are relevant.

The ultimate operating envelope of a plant is determined by the safety instrumented system (SIS) layer. The SIS is an independent system with its own sensors and logic system which hosts the executive limit. When the pressure measurement exceeds this limit, the switch sends a signal to the executive alarm to activate the interlock. The interlock initiates a series of process actions which include tripping of the heater and other related parts of the process to restore the pressure to a

safe value. Process operators are unable to override interlock actions until normal conditions are restored. In severe cases, an interlock can initiate an emergency plant-wide shut-down.

A flexible operating regime must stay well within the executive limits, because shut-downs are costly. As well as the SIS layer, there is also the process control system layer. In this layer, the low and high pressure alarms are activated by the pressure controller when the pressure reading is lower or higher than the pre-set limits. These limits are referred to as ‘process alarm limits’. Unlike in the SIS layer, process alarms are installed to warn process operators of a deviation in the system, so that the operators can manually make changes to restore normal conditions.

Every critical unit in the process is equipped with safety and protection systems which trigger process trips and emergency shut-downs when the operating conditions deviate beyond the pre-set limits. Since the effects of a set-point change propagate through the process, a variable operation strategy must consider these limits to avoid unnecessary trips. This work illustrates how the propagated effects of variable operation can be evaluated by considering an operating envelope defined by these limits.

III. THE PROPOSED APPROACH

The aim of this paper is to quantify the plant-wide capability for demand-side response by the analysis of pre-set limits on the process alarms. This paper will discuss the specifications required in Fig. 3 in order to implement an effective variable operation strategy.

Taking into account the continuous nature of industrial processes and propagated effects of a set-point change through the site, a variable operation strategy involves several characterisations. This paper generalises the methodology into three main steps:

- Selection of the *actuator* by examining the distribution of power consumption;
- Selection of a suitable *equivalent quantity* by using a process model;
- Quantification of *limits of set-point change* by analysing the process alarm limits.

A. Identifying the actuator

The *demand utilisation factor* (DUF) is introduced to examine the distribution of consumption within the process. This value indicates the power consumption of an individual unit relative to the consumption of the plant, given by:

$$DUF = \frac{\text{Nominal power consumption of unit}}{\text{Nominal power consumption of plant}} \quad (1)$$

Process units with larger DUF values represent the large consumers in the plant. These units are able to offer significant variations in the power consumption, and are therefore suitable for variable operation.

The actuators and their corresponding controlled variables for different process units are summarised in Table I.

TABLE I
ACTUATORS AND CONTROL PARAMETERS

Process unit	Actuator	Controlled variable
Pump	Variable speed drive (VSD) Inlet/outlet valve	Flow rate & outlet pressure
Compressor	VSD Inlet/outlet valve Inlet guide vanes	Flow rate & outlet pressure
Heat exchanger	Valve Thermostat	Flow rate Temperature
Reboiler	Valve	Flow rate

B. Selecting the appropriate equivalent quantity

The changes in the process variables can be expressed in terms of one useful quantity called the *equivalent quantity*. This quantity must be:

- Directly related to the actuator’s control parameters such as speed or flow rate;
- Representative of the changes in the process variables.

To find the suitable equivalent quantity, a process model is required. A process model is a system of mathematical equations used to describe the process. The equations show the relationship between process variables, and therefore can demonstrate how the effects of a set-point change propagate along the process. For example, a pressure drop equation (Darcy-Weisbach equation) is used to calculate the outlet pressure of a heat exchanger for different inlet pressure and flow rate values.

C. Quantifying limits of set-point change

The range of allowable operating set-points for the actuator is specified such that the resulting changes in process variables do not interfere with the process alarm limits specified on other process units.

Investigating the change on every process variable caused by a set-point change is very tedious, given the large number of process variables in any industrial process. This paper eliminates the necessity of investigating the changes in all variables by focusing on the process variables which have process alarm limits associated with them.

All process and executive alarm limits must be expressed as the *equivalent quantity*, and then compared to find the most stringent lower and upper equivalent limit values. These limits are referred to as the *critical limits*. Critical limits dictate the maximum and minimum allowable operating set-points for the actuator. These corresponding set-point values are found using the process model.

D. Plant Capability

Following the analysis on the safety and protection systems, the capability or the power reserve capacities of the plant through variable operation can be calculated:

$$R_{neg} = P_{max} - P_{nom} \quad (2a)$$

$$R_{pos} = P_{nom} - P_{min} \quad (2b)$$

Fig. 5. Simplified process topology of production line A in the heavy oil processing facility used in the case study

where R_{neg} and R_{pos} are the negative and positive reserve power capacities respectively, P_{max} and P_{min} are maximum and minimum possible power consumption of the plant respectively, and P_{nom} is the nominal power consumption.

The total power consumption (P_j) is calculated as follows:

$$P_j = \sum_{i=1}^n P_i(x_j) \quad \text{where } j \in \{max, min, nom\} \quad (3)$$

where P_i is the power consumption of process unit i , and n is the total number of process units. Due to the continuous nature of industrial processes, P_i changes when x_j changes.

IV. VARIABLE OPERATION IN AN OIL PROCESSING FACILITY

A. Oil processing platform

The case study is an ABB 800xA simulator representing a heavy oil processing facility. The facility is comprised of two wellhead platforms A and B, and a separation platform. There are two identical separation trains A and B on the separation platform. There are two production lines A and B on the facility, with production line A consisting of wellhead platform A and separation train A, and similarly for production line B. Fig. 5 shows the simplified process topology for production line A.

B. Characteristics of actuator

DUF analysis on the facility shows that the eight electrical submersible pumps (ESP) account for 77% of the total power consumption. Therefore, the ESPs were identified as the most suitable process unit to provide variable operation. For simplicity, only ESP A-1-1 is considered for variable operation. Each ESP is equipped with a variable speed drive (VSD) which allows the speed set-point to be directly varied.

Fig. 6 shows the operating characteristics of the ESP. The curves indicate different operating speeds, while the y- and x-axes indicate the outlet pressure and the flow rate through the pump respectively. All values on the figure are normalised with their respective nominal values. This graph illustrates how both flow rate and outlet pressure vary with a change in the speed set-point.

The relationship between speed and power consumption of a pump is given by the pump affinity law [15]:

$$P_2 = P_1 \left(\frac{\omega_2}{\omega_1} \right)^3 \quad (4)$$

Fig. 6. Pump characteristic map for ESP A-1-1

Fig. 7. Block diagram showing the dependency between process variables

where ω_i is the speed, P_i is the power consumption of the pump, and states 1 and 2 represent two different operating points.

C. Process model

Table II summarises the different types of equations used to represent the process. The derivation of the process model is beyond the scope of this paper.

TABLE II
EQUATION TYPES AND EXAMPLES

Process Variable	Equation type	Example
Flow rate (F)	Material balance	Flow rates of parallel pump units
Material composition (w)	Material balance with vapour-liquid equilibrium (VLE)	Composition of material in gaseous and liquid exit streams of a separation unit
Level (h)	Dynamic material balance with mass hold-up	Level inside a separation unit
Temperature (T)	Energy balance	Exit temperatures of a heat exchanger
Pressure (p)	Pump affinity law	Outlet pressure of a pump for a given speed and/or flow rate
	Darcy-Weisbach equation	Pressure drop across a heater

Based on the process model, flow rate of the ESP is selected as the *equivalent quantity*. It was observed that all process variables in the system can be expressed as a function of this flow rate, therefore proving its representativeness. Fig. 7 shows a simplified example of how the process model is used to find the relationship between the *equivalent quantity*, F_1 , and the different process variables.

Fig. 8. Comparison of alarm limits in terms of the equivalent quantity i.e. the flow rate of ESP A-1-1

Fig. 9. Plant capability for variable operation and demand-side response

D. Critical limits and plant capability

The lower or upper equivalent limits are calculated for every process alarm limit using the process model. Fig. 8 illustrates how the equivalent quantity is used to compare these limits. The figure shows three of the most critical alarms identified via the analysis on the safety and protection system.

Each block shows the range of ESP A-1-1 flow rates that will not interfere with the alarms on the respective process unit. The closed block represents the process unit which has both high and low process alarms, while the blocks with one end open represent process units having either a high or low process alarm.

Fig. 8 shows the critical limits of the process. The maximum flow rate is limited by the high flow alarm on the booster pumps, while the minimum flow rate is limited by the high pressure alarm on Heater 3. The allowable range for the flow rate of ESP A-1-1 is between 0.75 and 1.02 of the nominal.

The inverse relationship between flow rate and pressure in Heater 3 can be attributed to the preceding intermediate pumps. The pumps operate at a constant speed, thus a lower flow rate will result in a higher outlet pressure [15]. Since these effects propagate along the process, the pressure in Heater 3 will also be higher for a lower flow rate.

The maximum and minimum ESP speed limits, ω_{max} and ω_{min} respectively, are found using Fig. 6. Fig. 9 illustrates these results along with the corresponding total power consumptions. The values in the figure are normalised with their respective nominal values.

Operating the ESP below 94% of the nominal speed will trigger the high pressure alarm on Heater 3, while operating

higher than 101% will interfere with the high flow alarm on the booster pumps.

Through variable operation, a maximum reduction of 7.1% in power consumption can be achieved. This is equivalent to several MW of positive reserve capacity that the facility can offer without jeopardising operations on-site. However, there is a limited amount of negative reserve capacity that the facility can offer.

V. COST ANALYSIS AND DECISION-MAKING

In deciding the level of participation in DSR services, process automation engineers require tools which enable the cost of participation to be analysed. Load management strategies in industrial sites have been discussed numerous times in the literature [16]- [17]. The strategies focus on the decision on electricity purchase, formulated as an optimisation problem which consider the inter-dependence of industrial units and specific operational sequence of processes, as well as maximum demand constraints from the TSO.

The novel aspect highlighted in this paper is the importance of the process alarm limits. By considering these limits, there is less risk of interfering with the safety and protection system in the plant, which can lead to unwanted trips and cascaded shut-downs. While there are numerous protection systems installed in an industrial plant, the paper proposed a method to identify the critical limits of the process.

At the suggestion of one of the reviewers, this section comments upon how the methodology proposed in this paper might support a decision making process. The optimisation formulation presented below is adopted from [17], modified to include the work discussed in this paper.

$$\min_{x,y,z_1,z_2} C_e(x,y) - D(x,y) + z_1 C_r(x,y) + z_2 C_p(x,y) \quad (5a)$$

$$\text{s.t.} \quad \begin{aligned} f(x,y) &= 0 && \text{process model} \\ &&& \text{recovery and penalty models} \\ &&& \text{reserve payment model} \\ &&& \text{reserve request time} \end{aligned} \quad (5b)$$

$$g(x,y) \leq 0 \quad \begin{aligned} &\text{operational sequence} \\ &\text{production target and storage} \\ &\text{reserve minimum bid} \\ &\text{maximum load demand} \end{aligned} \quad (5c)$$

$$x_{min} \leq x \leq x_{max} \quad \text{actuator limits} \quad (5d)$$

$$z_1 + z_2 = 1 \quad \text{mutually exclusive cond.} \quad (5e)$$

$$y, z_1, z_2 \in \{0, 1\} \quad \text{integrality cond.} \quad (5f)$$

The objective function is to minimise the operating costs, which include electricity costs (C_e) and the costs of recovering lost production (C_r) or penalties for not meeting production targets (C_p), minus the payments for providing reserve services (D).

Adopting variable operation to this formulation, the decision variables can be modified such that x refer to the set-point on the actuator, while z_1 and z_2 are the binary variables which allow the operator to decide whether it is more cost-efficient to replenish production or to incur penalties respectively. The binary variable y is essential for ensuring that the process follows a certain operational sequence, as explained in [17].

The constraints x_{max} and x_{min} refer to the maximum and minimum allowable actuator set-points respectively, obtained from the analysis on the safety and protection systems as discussed in this paper. The operational sequence, maximum load demand, and production target and storage constraints are as discussed in [17].

The reserve minimum bid and request time constraints are the specifications by the TSO, while the payment model is typically market-based. Depending on the type of reserve service, the TSO has requirements on the minimum MW size of the reserve and the utilisation time. By including these specifications, process automation engineers are able to assess the suitability of their plant to participate in frequency control services.

Adding the constraints discussed above will make the formulation more realistic, as it involves both the specifications from the power system via the TSO and the physical limitations of the industrial process. Formulating and solving the optimisation study in the above format will be the study of a future work.

VI. CONCLUSIONS

This paper proposed a methodology which allows process automation engineers to assess the suitability of oil and gas processing plants to provide frequency control reserve services through variable operation. The methodology takes into account the continuity of industrial processes and the propagated effects of a set-point change throughout the industrial site by the analysis on the safety and protection systems.

The proposed methodology involves three main characterisations - the actuator which provides demand side response, the equivalent quantity, and the limits of set-point change. By analysing the pre-set limits on the process alarms, the maximum and minimum allowable operating set-points of the actuator can be specified. The reserve capacity of the plant can then be quantified by calculating the total power consumption of the plant when the actuator is operating at the minimum and maximum operating limits, and comparing these values to the nominal.

Application of the methodology was demonstrated on a case study representing an oil processing platform. Analysis on the process alarms enabled the maximum and minimum allowable speed set-point on the variable speed drive of the electrical submersible pump to be specified. Consequently, the positive and negative reserve capabilities of the facility were quantified. Through this analysis, the facility will be able to offer these reserve services without interfering with the safety and protection systems and jeopardising operations on-site.

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