Advanced Process Control aimed at energy efficiency improvement in process industries

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***Abstract*— This paper proposes an Advanced Process Control framework aimed at energy efficiency achievement and improvement in process industries. Model Predictive Control is the adopted control strategy: an architecture based on several cooperating blocks is proposed. The developed basic control framework has been enriched and customized for its installation on industrial processes. Steel industry billets reheating furnaces and cement industry clinker rotary kilns are examples of customized applications. With respect to the previous control systems, based on standalone controllers and/or plant operators manual conduction, strategic trade-offs between opposing objectives, e.g. production targets meeting, product quality specifications fulfillment, and energy efficiency achievement, have been ensured, together with significant improvements on process control.**

Keywords—Advanced Process Control; Model Predictive Control; clinker production; reheating furnace; energy efficiency.

I. INTRODUCTION

Energy efficiency and energy conservation are gaining importance as key components in many national and international political strategies to mitigate the impact of climate change, to improve security of energy supply, and to increase competitiveness. Energy represents a fundamental aspect in the modern technological development and its use affects the quality of the environment. For this reason, in process industries, *Green Economy* energy policies are needed that can guarantee a rational energy usage, with consumption and energy needs reduction. In the last years, energy efficiency certificates (Italian acronym TEE, also called "white certificates") have been introduced, in order to promote applications that meet environmental and energy standards. Through these certificates, government incentives can be obtained depending on energy consumption evaluation with respect to defined project baselines [1]. In process industry framework, Advanced Process Control (APC) solutions have increasingly shown their strong impact. APC strategies are the keys for stabilizing processes operations, exploiting classical local controllers combined in tailored architectures and/or adopting multivariable control techniques. In this way, the processes can more safely operate closer to their operating constraints, thus obtaining energy efficiency improvements [2]. A critical phase of an APC system design is represented by the choice of the control method. Model Predictive Control (MPC) approach represents a widely used control strategy [3], [4]. Exploiting a multivariable chemical, physical and economic modellization of the considered processes, the adoption of an MPC approach facilitates the reaching of the goal of stabilizing the processes operations, pointing toward the overcoming of the limitations of classical local controllers, e.g. PID (Proportional Integral Derivative) controllers manually run by plant operators [5]. Steel and cement industries are energivorous process industries. The involved process phases are characterized by high energy consumption; preliminary benefit studies can highlight process phases where energy efficiency margins can be estimated. APC solutions can be designed for process control and optimization [6], [7], [8], [9].

In this paper, two industrial APC solutions are proposed, customized for the control and the optimization of steel industry billets reheating furnaces and cement industry clinker rotary kilns. Their design is based on a common MPC framework. Each APC solution has been customized and a tailored cooperation between functional modules has been proposed. For example, the steel industry customization concerned the formulation of virtual sensors and the exploitation of adaptive MPC. The developed customized steel industry reheating furnaces control method has been awarded with an Italian patent [10]. After the installation of the developed controllers on industrial plants (steel and cement industries), satisfactory results have been achieved, in terms of optimal balance between energy and production specifications and observing process control requirements. The paper is organized as follows: Section II resumes the main features of the developed MPC-based APC framework. Section III and Section IV present the two customized industrial solutions, the first related to a steel industry case study and the second related to a cement industry case study. Field results are resumed in Section V, while Section VI reports the conclusion.

II. THE BASIC ADVANCED PROCESS CONTROL FRAMEWORK

A. APC Architecture

Fig. 1 depicts the basic APC architecture that represents the basis of the two industrial solutions proposed in this paper. At each control instant *k*, a Supervisory Control and Data Acquisition (*SCADA*) system supplies new measurements ($u(k-1)$, $d(k)$, $y(k)$) of the process variables: the Manipulated

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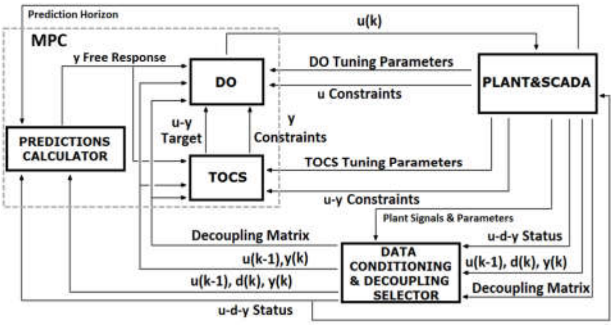

Figure 1. Scheme of the basic APC system.

Variables (MVs) set ($u \in \Re^{l_u \times 1}$), the measured input disturbances (Disturbance Variables, DVs) set ($d \in \Re^{l_d \times 1}$) and the Controlled Variables (CVs) set ($y \in \Re^{m_y \times 1}$). *Data Conditioning & Decoupling Selector* (*DC&DS*) block has been designed for checking bad conditions and local control loops faults, and for possibly conditioning field data. This block determines the process variables subset that has to be included in the MPC formulation at each control instant and, in addition, it defines the MVs to be exploited for the control requirements of each single CV [11]. All this information is supplied to a two-layer MPC block that exploits linear time invariant models. This block is based on the solution of two subsequent optimization problems and it includes a *Predictions Calculator* module. At the upper layer, a steady-state module, called Targets Optimizing and Constraints Softening (*TOCS*) module, solves a preliminary optimization problem; hence, *TOCS* module results are forwarded to the lower layer, constituted by a basic MPC Dynamic Optimizer (*DO*) module. This module, solving a second optimization problem, computes the MVs value $u(k)$ to be applied to the plant at the current control instant. *TOCS* and *DO* modules exploit the same basic linear model of the process to be controlled. The overall MPC computation is based on the *receding horizon* concept [4].

B. *MPC modules*

As stated in the previous subsection, the developed MPC strategy is based on two main modules, i.e. *DO* and *TOCS*. These modules solve an optimization problem formulated as Quadratic Programming (QP) or Linear Programming (LP) problem. *DO* and *TOCS* cost functions (to be minimized) are represented by (1) and (3), respectively, while expressions in (2) and (4) represent the related constraints sets.

$$V_{DO}(k) = \sum_{i=1}^{H_p} \|\hat{u}(k+i-1|k) - u_t(k+i-1|k)\|^2_{S(i)} + \\ + \sum_{j=1}^{m_y} \sum_{i=H_{w_j}}^{H_p} (Q_{(j,j)}(i) \cdot \left(\hat{y}_j(k+i|k) - y_t(k+i|k)\right)^2) + \\ + \sum_{i=1}^{H_u} \|\Delta\hat{u}(k+M_i|k)\|^2_{\mathcal{R}(i)} + \left\|\varepsilon_{y\_DO}(k)\right\|^2_{\rho_{y\_DO}} \tag{1}$$

subject to

$$\begin{aligned} &\text{i. } lb_{du\_DO}(i) \le \Delta\hat{u}(k+M_i|k) \le ub_{du\_DO}(i), i = 1, \dots, H_u \\ &\text{ii. } lb_{u\_DO}(i) \le \hat{u}(k+M_i|k) \le ub_{u\_DO}(i), i = 1, \dots, H_u \\ &\text{iii. } lb_{{y\_DO}_j}(i) - \gamma_{{lby\_DO}_j}(i) \cdot \varepsilon_{y\_DO}(k) \le \hat{y}_j(k+i|k) \le \\ &\quad ub_{{y\_DO}_j}(i) + \gamma_{{uby\_DO}_j}(i) \cdot \varepsilon_{y\_DO}(k), \;\; j = 1, \dots, m_y, \;\; i = H_{w_j}, \dots, H_p \\ &\text{iv. } \varepsilon_{y\_DO}(k) \ge 0 \end{aligned} \tag{2}$$

$$V_{TOCS}(k) = {c_u}^T \cdot \Delta\hat{u}_{TOCS}(k) + {\rho_{y\_TOCS}}^T \cdot \varepsilon_{y\_TOCS}(k) \tag{3}$$

subject to

$$\begin{aligned} &\text{i. } lb_{du\_TOCS} \le \Delta\hat{u}_{TOCS}(k) \le ub_{du\_TOCS} \\ &\text{ii. } lb_{u\_TOCS} \le \hat{u}_{TOCS}(k) \le ub_{u\_TOCS} \\ &\text{iii. } lb_{y\_TOCS} - \gamma_{lby\_TOCS} \cdot \varepsilon_{y\_TOCS}(k) \le \hat{y}_{TOCS}(k) \le \\ &\qquad \le ub_{y\_TOCS} + \gamma_{uby\_TOCS} \cdot \varepsilon_{y\_TOCS}(k) \\ &\text{iv. } \varepsilon_{y\_TOCS}(k) \ge 0 \end{aligned} \tag{4}$$

Both modules exploits process variables predictions over a prediction horizon H_p. *DO* module takes into account values of $\hat{u}(k+i-1|k)$ and $\hat{y}_j(k+i|k)$ on the entire H_p (see (1)- (2)), while *TOCS* module considers the steady-state (H_p) predictions ($\hat{u}_{TOCS}(k)$ and $\hat{y}_{TOCS}(k)$ in (3)-(4)). The predictions components that do not depend on the MVs future values are computed by *Predictions Calculator* module. The future MVs values are $\Delta\hat{u}(k+M_i|k)$ on a control horizon H_u in (1)-(2) and $\Delta\hat{u}_{TOCS}(k)$ in (3)-(4). Both *DO* and *TOCS* modules take into account process variables constraints (see (2) and (4)): MVs constraints are considered as inviolable (*hard*) constraints, while CVs (*soft*) constraints can be relaxed in critical conditions. For this purpose, slack variables vectors $\varepsilon_{y\_DO}(k)$ and $\varepsilon_{y\_TOCS}(k)$ have been introduced in (1)-(4). *TOCS* module, taking into account minimization and/or maximization goals for MVs (see c_u in (3)), solves the designed LP problem. Optimal steady-state targets and constraints for *DO* module are thus obtained (Fig. 1, *u-y Target* and *y Constraints*). *DO* module, taking into account different control objectives (see the first three terms in (1)), solves the formulated QP problem, computing the optimal control sequence. At each control instant, only the first term of the computed sequence is forwarded to the plant (Fig. 1, *u(k)*).

III. STEEL BILLETS REHEATING FURNACES APC SYSTEM

Fig. 2 shows the production chain of a steel industry. Raw materials are processed obtaining small steel bars, e.g. billets. Billets, at different temperatures, enter in a reheating furnace where they are suitably reheated so to meet the specifications required for the subsequent rolling phase [6]. The basic APC system described in the previous section has been customized so to be applied on the *Reheating Phase* (Fig. 2). This phase represents a crucial step that strongly influences the whole plant energy efficiency and products quality. Within the furnace, pushers move billets according to the defined furnace production rate; in this case, the reheating furnace is denoted as *pusher type*. In the present paper, this furnace typology is proposed as case study related to steel industry (Fig. 3). In Fig. 3 a synoptic of the developed Graphical User Interface (GUI) is shown. Three main furnace areas can be observed (from left to right): *Preheating*,

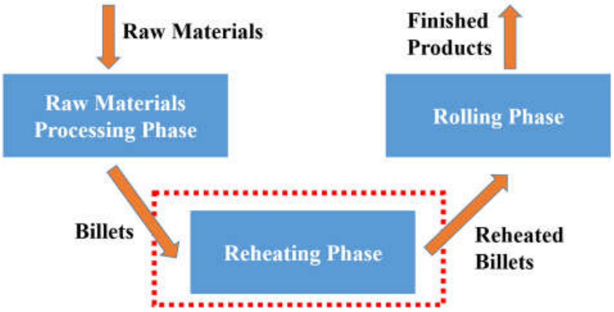

Figure 2. General steel industry workflow.

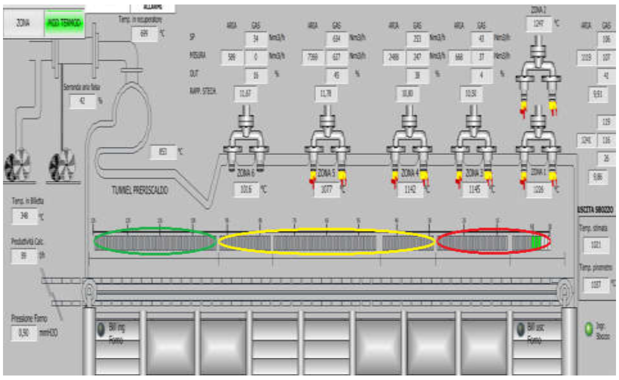

Figure 3. Pusher type reheating furnace schematic representation.

TABLE I. FURNACE AREAS FEATURES

Area	Billets Number	Temperature	Acronym [*Units*]
Preheating	38	Tunnel Temp.	*Tun* [°C]
Heating	64	Zone 6 Temp.	$Temp_6$ [°C]
		Zone 5 Temp.	$Temp_5$ [°C]
		Zone 4 Temp.	$Temp_4$ [°C]
Soaking	34	Zone 3 Temp.	$Temp_3$ [°C]
		Zone 2 Temp.	$Temp_2$ [°C]
		Zone 1 Temp.	$Temp_1$ [°C]

Heating and *Soaking*. Table I summarizes the furnace areas configuration with the related zones and the billets maximum number. The considered process, before the introduction of the developed APC system, was controlled through local PID temperature controllers manually driven by plant operators. Furthermore, a key aspect was the lack of billets temperature measurements inside the furnace: the billets temperature was available through optical pyrometers only at the furnace inlet and outlet. This fact, together with the multivariable and strongly time varying nature of the process, required a strong effort to the plant operators in ensuring an acceptable billets heating; consequently, energy efficiency aspects were difficultly optimized.

A. Replacement of the local controllers

The first step performed for the improvement of the process energy efficiency and control performances has been the substitution of the local standalone temperature controllers with a two-layer MPC system based on linear models (Section II). In this way, a multivariable constrained approach has been guaranteed for the zones temperature control. For the setup of the two-layer MPC strategy, fuel flow rates and stoichiometric ratios of each furnace zone with an own burners set (all furnace zones except tunnel) have been selected as MVs (u, $l_u = 12$), while DVs group (d, $l_d = 3$) includes the furnace production rate and the furnace and air pressures. The involved CVs have been denoted as *zones* Controlled Variables (zCVs, y): furnace zones temperature and temperature difference between adjacent furnace zones are zCVs examples. Through an identification procedure, linear time invariant asymptotically stable zCVs-MVs/DVs models have been obtained. The just described MPC strategy has been denoted as *zones* APC mode: exploiting positive *TOCS* c_u weights (see (3)), optimal steady-state targets complying with process constraints are provided to *DO* module. *DO* module, taking into account MVs and zCVs constraints, guarantees *TOCS*-supplied targets approaching, also monitoring the magnitude of the control moves [12].

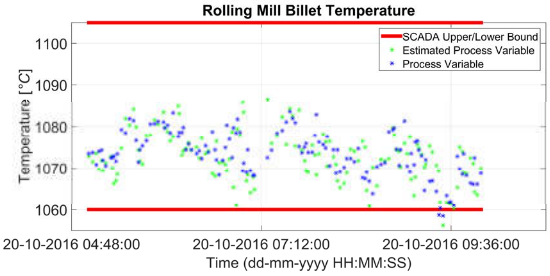

Figure 4. Example of virtual sensor performances.

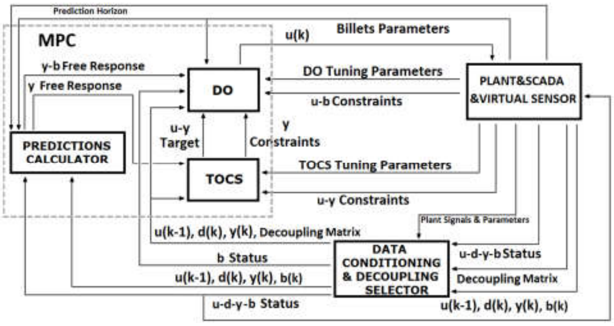

Figure 5. "i.Process | Steel – RHF" architecture.

B. An additional APC mode

In order to really approach the most profitable process operating points, a virtual sensor has been formulated that estimates the billets temperature inside the furnace. The virtual sensor implements a first principles nonlinear model equipped with adaptation strategies of the related uncertain coefficients [10], [13]. Fig. 4 shows the billets temperature at the furnace outlet pyrometer position (for further details on this figure, see Section V): a comparison between the pyrometer measurements (blue stars) and the virtual sensor estimations (green stars) are reported. The reliable performances of the developed virtual sensor have motivated the inclusion of the billets temperature as an additional CVs group (bCVs, b) in the control framework. A Linear Parameter Varying (LPV) model has been accordingly derived for each billet inside the furnace [13]. Suitable tracking terms and constraints related to the bCVs have been introduced in (1)-(2). This additional control mode has been denoted as *adaptive* APC mode and it represents the main control mode. Fig. 5 represents the global APC architecture (note the additional components with respect to Fig. 1): the control system has been called as "i.Process | Steel – RHF".

IV. CLINKER PRODUCTION APC SYSTEM

Different sub-processes are involved in the cement industry workflow (Fig. 6). For example, a dry process produces hydraulic binders: the action of mills allows obtaining a finely ground power by raw materials. Then, a baking procedure in a rotary kiln on the obtained raw meal gives rise to the clinker. The desired type of cement is obtained by clinker processing together with other components, e.g. calcium sulfate or pozzuolan. Fig. 6 schematically depicts the cement industry workflow. A significant sub-process in terms of energy

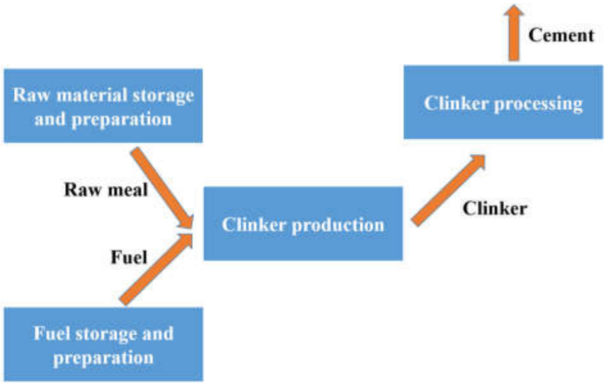

Figure 6. General cement industry workflow.

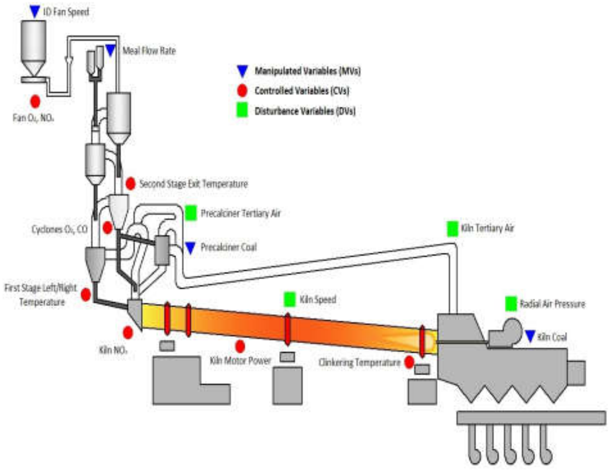

Figure 7. Clinker production phase.

efficiency achievement and product quality preserving is represented by the clinker production phase. The clinker is the main component of the cement and the final part of its production takes place in a rotary kiln. The basic APC system described in the Section II has been customized for its application on the clinker production phase.

Fig. 7 schematically represents the considered real case study. A four-stage suspension pre-heater is fed with raw meal (Fig. 7, left side). The suspension pre-heater is characterized by four cyclones stages (note the so-called cyclones tower on the left side of Fig. 7). Raw meal is then processed through a preheating/drying phase (typical temperatures range: 650 [°*C*] - 900 [°*C*]) that involves also exhaust gas from downstream zones that is pulled by an induced draft (ID) fan (Fig. 7, left side). Raw meal and exhaust gas are subject to separation and reunification procedures in each cyclone stage. The baking procedure takes place in a rotary kiln (Fig. 7) that is a sloped steel cylinder where the primary combustion process is triggered by an air/fuel (coal) burner located near the kiln outlet. Another burner (the precalciner burner, located between the suspension pre-heater and the kiln) contributes to combustion reactions. At its exit by the kiln, clinker is characterized by a temperature of about 1200 [°*C*]; for this reason, a cooler reduces the clinker temperature for the subsequent grinding phase.

A. *Control specifications and process modelling*

In the clinker production phase, there are many objectives to consider: thermodynamical, environmental, mechanical and quality. The main process variables to keep under control are the oxygens and carbon monoxide concentrations, the cyclones and kiln zones temperatures, the nitrogen oxides levels, the kiln torque, and the free lime concentration. In the considered case study, the mentioned process variables are measured through sensors and/or laboratory analysis. A particular feature is represented by the free lime analysis. While the other process variables measurements are continuously available, the free lime analysis is performed on clinker samples (collected at the rotary kiln outlet) four time a days. Before the introduction of the developed customized APC system, the clinker production phase was driven by plant operators based on their experience and skills. Plant operators suitably set up the set-points for meal flow rate, kiln and precalciner coal, and ID fan speed; in this way, they try to keep the mentioned critical process variables inside the desired operating zones, taking into account also the action of rotation kiln speed, kiln and precalciner tertiary air and radial air pressure. Large inertia, pure hysteresis, nonlinearity and strong coupling characteristics affect the considered process, so plant operators preferred control objectives to optimization ones. Because of the described process features and specifications, the APC framework described in Section II (Fig. 1) has been adopted and customized for the clinker production phase control and optimization. The developed controller, called as "i.Process | Cement", replaced the described operators' conduction. The position of the adopted MVs, DVs and main CVs has been depicted in Fig. 7. Table II shows the main CVs, together with the measurement type (sensor/analyzer). MVs and DVs are reported in Table III. A black-box approach has been adopted for the identification phase, obtaining linear time invariant asymptotically stable strictly proper minimum phase models with delays.

TABLE II. MAIN CONTROLLED VARIABLES (CVS)

Variable Name	Sensor/Analyzer	[*Units*]
Cyclones Oxygen	Analyzer	[*%*]
Fan Oxygen	Analyzer	[*%*]
Kiln Nitrogen Oxides	Analyzer	[*ppm*]
Fan Nitrogen Oxides	Analyzer	[*ppm*]
Cyclones Carbon Monox.	Analyzer	[*%*]
First Stage Right Temp.	Sensor	[°*C*]
First Stage Left Temp.	Sensor	[°*C*]
Second Stage Exit Temp.	Sensor	[°*C*]
Kiln Motor Power	Sensor	[*kW*]
Clinkering Temperature	Sensor	[°*C*]

TABLE III. MANIPULATED VARIABLES (MVS) AND DISTURBANCE VARIABLES (DVS)

MV [*Units*]	DV [*Units*]
Meal Flow Rate [*t/h*]	Rotation Kiln Speed [*rpm*]
Kiln Coal [*kg/h*]	Kiln Tertiary Air [*%*]
Precalciner Coal [*kg/h*]	Precalciner Tertiary Air [*%*]
ID Fan Speed [*rpm*]	Radial Air Pressure [*mbar*]

B. *Customization example*

Some customizations for the process at issue have been developed on the basic APC framework described in Section II. For example, examining Table II, redundancy on certain CVs can be observed. Considering nitrogen oxides, the main nitrogen

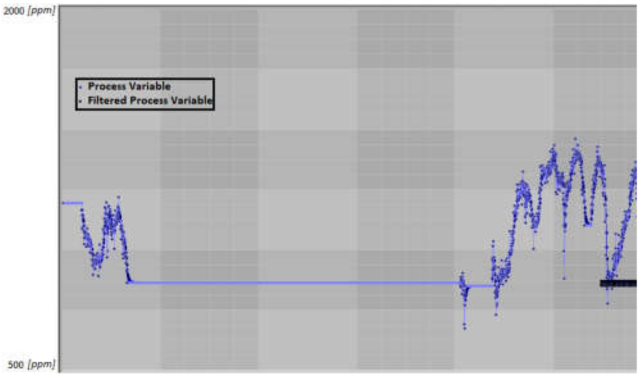

Figure 8. Malfunction related to the kiln nitrogen oxides analyzer.

oxides analysis to be kept under control is the kiln nitrogen oxides; however, the analyzer related to this variable may be subject to malfunctions (Fig. 8). In these situations, the kiln nitrogen oxides control can be replaced by the control of the other nitrogen oxides levels (e.g. fan nitrogen oxides). This logic example has been implemented in the basic APC framework thanks to the *DC&DS* block (Fig. 1) functions. This block, through a suitable tuning of the bad detection parameters, allows obtaining the subset of MVs, DVs and CVs to be eventually included in the control problem.

V. REAL RESULTS

The two industrial products described in Sections III-IV, i.e. “i.Process | Steel – RHF” and “i.Process | Cement”, have been installed on the described real plants in June 2015 and in December 2014/January 2015, respectively.

A. Approaching the processes operating limits

Fig. 4 and Fig. 9-11 represents a real plant configuration under “i.Process | Steel – RHF” control. A period equal to five hours is taken into account. Fig. 9 represents the furnace production rate in the considered time window (note the high variability). Fig. 10 represents the input temperature of the billets that will enter the furnace in the considered period (15 [°*C*]-80 [°*C*]); the billets that are already in the furnace are characterized by temperatures in the range 30 [°*C*]-1100 [°*C*]. Furthermore, it is required that the billets reach the rolling mill stands with a temperature in the range 1060 [°*C*]-1105 [°*C*] (Fig. 4, straight red lines). An optimized usage of fuel flow rates is achieved: it can be noted on the inputs of the billets LPV model (Fig. 11). In Fig. 9, an high variability of the furnace production rate can be noted: an energy saving strategy is ensured by optimal adjustments on the zones temperature. In fact, notwithstanding the high variability of the furnace production rate and the not constant future billets inlet temperature, the exited billets reach the rolling mill area with temperatures that approach the required temperature lower bound (Fig. 4).

Fig. 12-13 depict a comparison on cyclones oxygen and kiln nitrogen oxides control before and after “i.Process | Cement” activation (about three weeks performance test in the commissioning phase). More profitable operating points are guaranteed for these critical CVs: about -39 [%] and -32 [%] standard deviation variation (respectively) has been obtained, together with about +3 [%] and -15 [%] mean value variation.

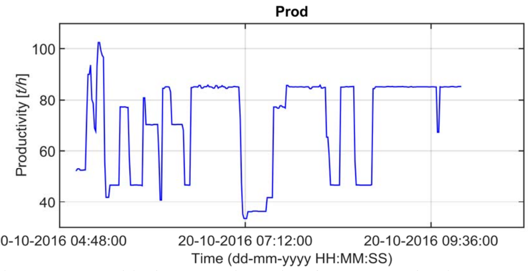

Figure 9. Steel industry real results: furnace production rate trends.

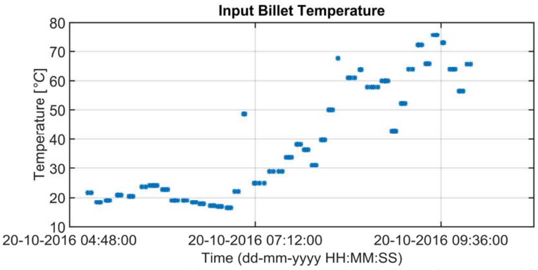

Figure 10. Steel industry real results: billets furnace inlet temperatures trends.

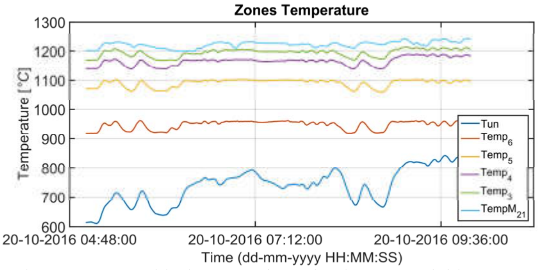

Figure 11. Steel industry real results: bCVs model inputs trends.

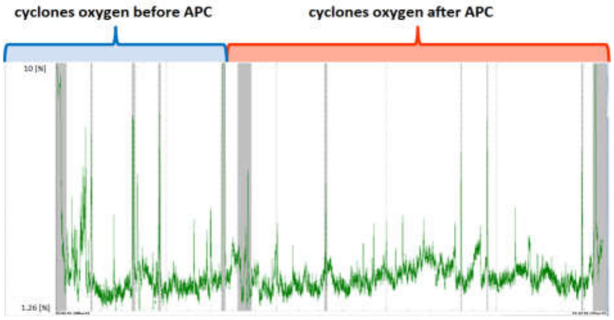

Figure 12. Cement industry real results: cyclones oxygen trends before and after “i.Process | Cement” activation.

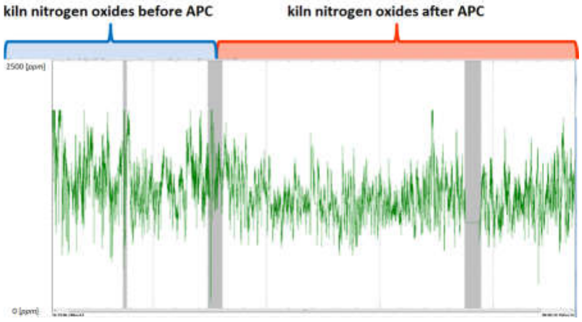

Figure 13. Cement industry real results: kiln nitrogen oxides trends before and after “i.Process | Cement” activation.

B. *Focusing on the fuel specific consumption*

The process control improvements after the installation of the two industrial products allowed working closer the operating limits. This important aspect has been also registered from a fuel specific consumption point of view. Fig. 14-15 show an example of fuel specific consumption performances after the installation of the developed APC systems. Fig. 14 refers to "i.Process | Steel – RHF" performances on the considered billets reheating furnace (Italian steel plant). The computed project baseline (red) that may vary with the furnace hot charge is compared to the official fuel specific consumption (blue) during the first year of operation ([Sm^3/t]). After about two years since the first start-up, the specific consumption has been lowered of about 2 [%]. Moreover, a service factor about equal to 95 [%] has been registered. Fig. 15 refers to "i.Process | Cement" performances on the considered clinker production phase (Italian cement plant). It depicts a comparison related to the fuel specific consumption ([*kg/t*]) before and after the installation of the developed controller on the real plant. Red dashed line indicates the fuel specific consumption mean value computed on a period of one year before the installation of the APC system; after about eight months since the first start-up, a 2.2 [%] decrease has been registered. Thanks to the specific consumption performances and, more generally, to the energy efficiency achievement and improvement (that involves also emissions reduction), Italian energy efficiency certificates (Italian acronym TEE, also called "white certificates") have been obtained in both case studies.

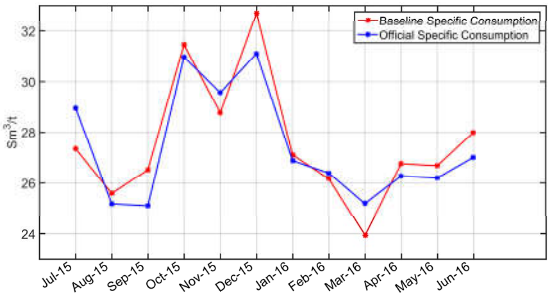

Figure 14. Steel industry real results: comparison between baseline and official specific consumption.

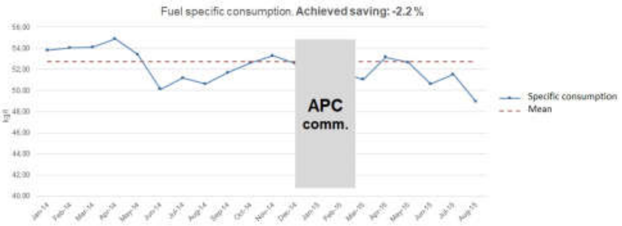

Figure 15. Cement industry real results: specific consumption before and after APC activation.

VI. CONCLUSION

In this paper, a Model Predictive Control (MPC)-based Advanced Process Control (APC) framework for energy efficiency achievement and improvement in process industries has been proposed. Steel industry billets reheating furnaces and cement industry clinker rotary kilns have been considered as case studies. A customized APC solution for both processes has been developed, obtaining "i.Process | Steel – RHF" and "i.Process | Cement" APC systems. Each APC solution, based on the cooperation of suitable functional modules, has been tailored for the related process.

The application of the developed control systems on steel and cement plants has guaranteed a better trade-off between energy and production specifications, when compared to the previous control systems, based on standalone controllers and/or plant operators manual conduction. Improvements on the control of the main process variables have been achieved after the installation on the real plants. The process control improvements allowed the reduction of the fuel specific consumption, obtaining energy efficiency certificates.

The formulated control method for steel industry reheating furnaces has been awarded with an Italian patent [10].

Future work could be focused on the attempt of the extension of the processes phases under the control of "i.Process | Steel – RHF" and "i.Process | Cement" APC systems.

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