High Level Optimization of a Steel Industry Reheating Furnace

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Abstract. The present paper describes the design and the installation of an Advanced Process Control (APC) system on a steel industry billets reheating furnace located in an Italian steel plant. The installed APC system acts as a high level optimizer that manipulates the furnace zones temperature set points. A Model Predictive Control (MPC) strategy represents the core of the control algorithm that exploits a tailored furnace mathematical model. Some critical aspects in the steel industry reheating furnaces control, e.g. the management of the change of billets furnace inlet temperature and of the change of the furnace production rate, are addressed. The designed controller, which is a proprietary patented control solution (Industry 4.0 compliant), has improved the previous furnace manual conduction. A safer approach to process operating limits has been targeted, together with a significant improvement on process control. In particular, reaching more profitable zones temperature configurations, the optimization of all operating conditions (furnace normal production, furnace planned/unplanned downtimes) is guaranteed. The benefits produced by the commissioning of the proposed APC system have been proved in terms of fuel specific consumption reduction, evaluating the most important production periods: a 2% fuel specific consumption reduction has been certified while maintaining the needed reheating profile for the reheated billets.

Keywords: reheating furnace, Model Predictive Control, energy saving.

1 Introduction

In steel industry, before hot rolling, it is necessary that the workpieces (e.g. billets, slabs, blooms) be homogeneously reheated at a temperature between 1100 ºC and 1200 ºC. The main production phases in a steel industry are depicted in Fig. 1: 1) the production of the workpieces; 2) the reheating of the workpieces in a reheating furnace; 3) the processing of the reheated workpieces in the rolling mill stands, in order to obtain the desired final products (e,g, tube rounds, iron rods) [1], [2], [3], [4].

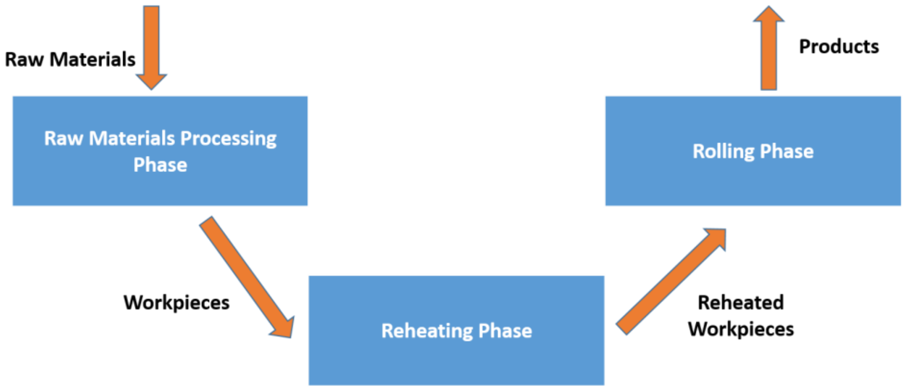

Fig. 1. Main steel industry production phases.

The *Reheating Phase* takes place in a reheating furnace where air/fuel burners trigger combustion reactions. Reheating furnaces are among the most energy-demanding units in the steel industrial process; the *Reheating Phase* represents a crucial phase both from an energy efficiency and from product quality point of view: the desired workpieces reheating profile has to be achieved in working with both hot and cold material at furnace inlet.

A reheating furnace is generally divided in different areas, and the temperature of each area is regulated by PID (Proportional Integral Derivative) controllers that receive temperature set points and influence the air/fuel combustion control. Many critical aspects characterize the reheating furnace control at the various levels of the control hierarchy. For example, at low control level, the choice of the burners' type can play an important role, while, at higher levels, the management of the temperature set point of the different furnace areas can affect the energy efficiency and product quality levels.

In many reheating furnaces, the temperature set points of the PID controllers are manually set by plant operators, based on their experience and skills. The multivariable and nonlinear time varying nature of the process, together with the many aspects to be taken into account (e.g. the change of the workpieces furnace inlet temperature and the change of the furnace production rate), have attracted the interest of the researchers and of the plant technicians. In literature, for reheating furnaces high level control and optimization, different Advanced Process Control (APC) solutions have been proposed. A furnace transient nonlinear model and the related control system have been reported in [5], where all the advantages of a model-based control and optimization strategy are also specified. A nonlinear Model Predictive Control (MPC) approach has been proposed in [6]-[7], where a slabs reheating furnace is considered. A first principles mathematical model has been designed and exploited by an MPC algorithm in order to ensure the desired slabs final exit temperature. In [8], a neural network approach is exploited: a recurrent neural network for zones temperature estimation and a heat transfer model for billets temperature prediction are integrated in order to generate an intelligent decoupling control strategy. The heating process that take place in a reheating furnace is modelled through a double model in [9], and the related double model slab tracking control system is presented. A nonlinear optimization problem based on genetic algorithms approach is reported in [10], with the goal of minimizing fuel cost while satisfying a desired discharge temperature. In [11], a model-based multi-objective optimization strategy using genetic algorithm is adopted to determine an optimal temperature trajectory of the workpieces to minimize an appropriate cost function.

Some aspects of a patented control method developed by the authors has been reported in [12], together with the results obtained in a pusher type billets reheating furnace located in an Italian steel plant. The developed furnace model has been presented [13]. Multiple control modes have been described for the billets temperature control and optimization: the main control mode is characterized by an adaptive model predictive controller. In [14]-[15] other aspects, e.g. the stoichiometric ratios optimization, have been addressed. In [12], [14], [15], the manipulated variables of the APC system were directly the fuel flow rates: the APC system had broken the cascade configuration between the PID temperature controllers and the air/fuel combustion control.

In this paper, a new configuration of the patented control algorithm is proposed by the authors: the manipulated variables of the APC system are represented by the temperature set points of the PID controllers. The proposed APC system provides a high level optimization of the temperature set points. The considered reheating furnace is pusher type; these furnaces are capable of high production rates. The proposed reheating furnace is characterized by a wide range of variability of the workpieces furnace inlet temperature (0-910 °C) and of the furnace production rate (0-170 tons per hour). Significant field results are discussed, focusing on control accuracy and energy efficiency aspects.

The paper is organized as follows: Section 2 presents the process description. Section 3 reports the APC system features, focusing on the process model and on the control strategy. Field results are presented in Section 4, while conclusions are reported in Section 5.

2 Case study: an Italian steel industry reheating furnace

Fig. 2 shows the tailored Graphical User Interface (GUI) on the Supervisory Control and Data Acquisition System (SCADA). It schematically represents the reheating furnace, located in an Italian steel plant, where the developed high level APC system has been installed. The considered furnace is a pusher type reheating furnace that may contain up to 138 billets (m_b=138 billets): the billets enter the furnace one or two at a time from the left side; pushers trigger the billets movement from the entrance to the exit of the furnace. The billets furnace inlet temperature can be very different (in the range 0 – 910 °C). Furthermore, the charge scheduling is not known a priori, because it depends on many aspects, e.g. the continuous casting status. Two optical pyrometers located near the furnace entrance measure the billets furnace inlet upper surface temperature. The furnace production rate can reach 170 tons per hour. As can be noted in Fig. 2, four areas characterize the reheating furnace (ordered form left to right). The first three areas are characterized by a single heating zone (from left to right: zone 1, zone 2, zone 3). Zone 1 characterize the preheating process, while the billets reheating process takes

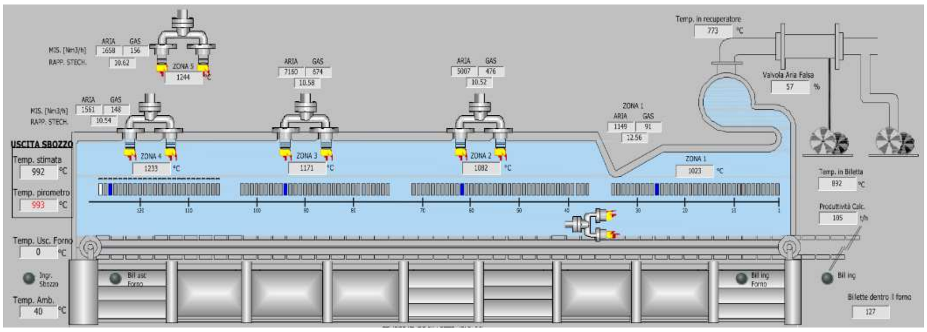

Fig. 2. Schematic representation of the considered billets reheating furnace.

place in zones 2-3. The soaking process takes place in the last furnace area, composed by two different heating zones that are disposed at the right and left side, with respect to the furnace axis (zones 4-5). Zone 5 heats the billets tail, while zone 4 heats the billets head. Zones temperature is measured by thermocouples. In the furnace, no measurement of billets temperature is available. After their exit from the furnace, the billets enter the roughing rolling mill stage area, characterized by six stands. Billets temperature after their exit from the furnace is measured by an optical pyrometer located after the first three rolling mill stands; an example of the exit temperature range is 950-1050 °C. The billets temperature specification at the furnace exit differs based on the final product type. Table 1 describes the main billets features, while Table 2 reports some aspects related to the furnace zones.

Table 1. Billets features.

Feature	Value
Height	0.14 m
Width	0.14 m
Length	12.2 m
Mass	1.87 tons
Inlet Temperature Range	0-910 °C
Exit temperature Range	950-1050 °C

Table 2. Furnace zones features.

Furnace zone	Billets number	Temperature set point range
Zone 1	38	825-1020 °C
Zone 2	40	925-1090 °C
Zone 3	33	1025-1180 °C
Zones 4-5	27	1115-1240 °C

The furnace combustion is regulated by local PID temperature controllers that act on air/fuel of the related zone. Before installing the proposed high level APC system, PID temperature set points were managed by plant operators based on their experience and skills. Due to the wide range of variability of the billets furnace inlet temperature (0-910 °C) and of the furnace production rate (0-170 tons per hour), significant margins on energy efficiency improvement have been detected during the furnace benefit study. In particular, during the furnace benefit study, energy efficiency improvement directions have been detected, e.g. the reduction of PID temperature set points while respecting the billets temperature specifications. The reduction of PID temperature set points causes the expected reduction of the fuel specific consumption (see Section 3-4).

3 High level APC system

A high level optimizer for a steel industry billets reheating furnace must ensure a zones temperature set points configuration that guarantees the desired billets furnace exit temperature. The energy efficiency achievement and improvement are strictly related to the minimization of the fuel consumption and to the furnace production rate maximization: for this reason, a commonly used Key Performance Indicator (KPI) is represented by the fuel specific consumption.

3.1 Process model

As already specified, a very crucial point in a reheating furnace is the absence of billets temperature measurements within the reheating furnace. For this reason, a virtual sensor that estimates the billets temperature profile from their entrance into the furnace to the end of the rolling mill stands has been formulated. A first principles nonlinear model represents the core of the virtual sensor; the unknown coefficients are online estimated and adapted based on the measurements provided by the optical pyrometer located after the first three rolling mill stands [13]. A fundamental requirement for a precise temperature estimation is to track the billets position during their path within the furnace: a tracking algorithm has been integrated within the virtual sensor formulation, based on signals (e.g. photocells) provided by plant Programmable Logic Controller (PLC). The temperature inputs of the virtual sensor are represented by the 1-2-3 zones temperatures and by the mean between 4-5 zones temperature. An example of the virtual sensor on line estimation performances has been reported in Fig. 3, while the related zone temperatures have been represented in Fig. 4. More specifically, in Fig. 3 the virtual sensor estimation (blue) is compared to the measurement provided by the optical pyrometer located after the first three rolling mill stands (red). In the considered period, the furnace inlet temperature of the considered billets varies in the whole range 0-910 °C. During furnace normal production, the root mean square error related to the virtual sensor billets temperature estimation after the first three rolling mill stands is in the range 8 – 15 °C (about 1% of the optical pyrometer measurement range).

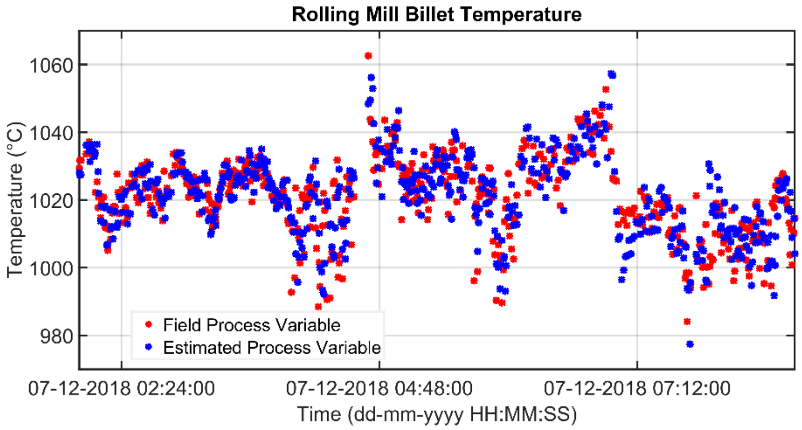

Fig. 3. Virtual sensor estimation performances.

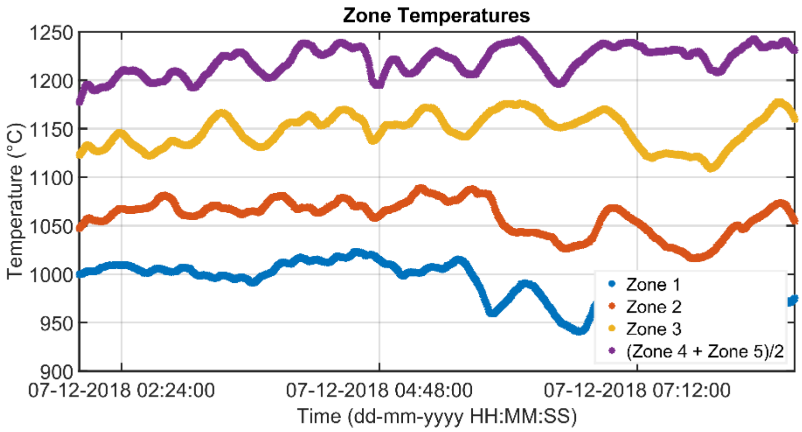

Fig. 4. Virtual sensor inputs.

The developed virtual sensor nonlinear model has been suitably linearized in order to be exploited in the proposed APC formulation (see Section 3.2) based on linear models. As typical in industrial control applications, a first crucial step is the proper selection of the inputs, or Manipulated Variables (MV), and of the outputs, or Controlled Variables (CV).

In the considered APC application, MVs are the zone temperature set points (u: for example, Zone 1 set point) of each furnace zone. CVs have been divided into two subgroups: the furnace variables (y: for example, furnace zones temperature, smoke-exchanger temperature) and the billets variables (b: furnace billets temperatures). In order to obtain u-y models, tailored step test procedures have been executed on the furnace (black-box approach). Linear Time Invariant asymptotically stable models have been obtained. Fig. 5 shows the performances of the estimated model related to furnace zone 3. The model output (blue line) is compared to the measurement of the zone 3

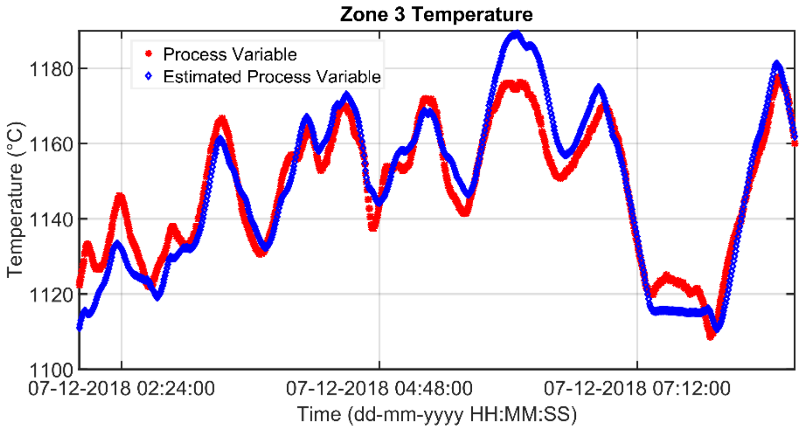

Fig. 5. Zone 3 model performances.

Table 3. *u-y* models gain signs.

Process Variable	Zone 1 SP	Zone 2 SP	Zone 3 SP	Zone 4 SP	Zone 5 SP
Zone 1 Temperature	+	+			
Zone 2 Temperature		+	+		
Zone 3 Temperature			+	+	+
Zone 4 Temperature			+	+	+
Zone 5 Temperature				+	+

temperature (red line). Table 3 shows the sign of the gains that characterize some of the obtained transfer functions. Empty cells indicate that no significant influence has been observed between the variables. In order to find a proper model between *u* and *b*, the *u-y* models are used together with the linearized virtual sensor model.

3.2 Control strategy

The proposed high level APC system is based on Model Predictive Control (MPC) techniques [16]. The MPC control strategy exploits the formulated furnace mathematical model to compute long-range predictions. The APC system architecture is represented in Fig. 6. The SCADA system provides signals and parameters at each control instant; Data Conditioning & Decoupling Selector (DC&DS) block performs several tasks, e.g. signals validation; the MPC block computes the optimal inputs ($u(k)$) to be supplied to the reheating furnace at each control instant.

The developed high level APC system has been based on two control modes:

- *adaptive* APC mode: this mode makes use of both identified *y-u* linear models and first principles *b-u* linearized model and exploits billets virtual sensor information. An adaptive two-layer linear MPC strategy has been formulated. For details, see [12];

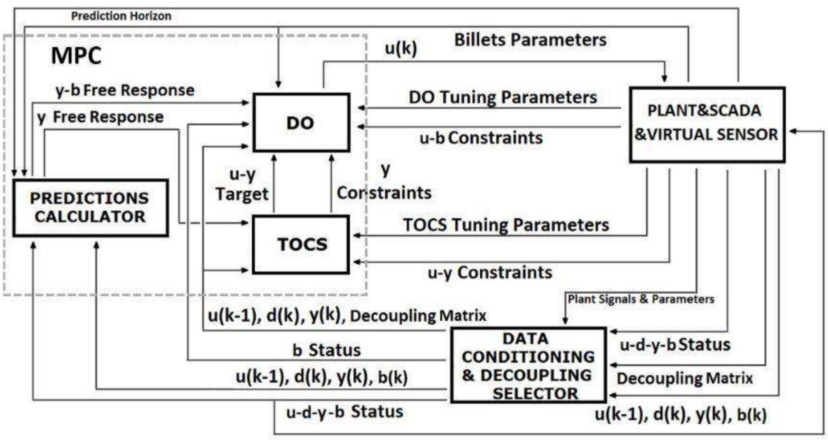

Fig. 6. High level APC system architecture.

- *zones* APC mode: *y-u* linear models are used within a two-layer linear MPC strategy [14], [15].

The developed MPC strategy is based on a two-layer architecture, represented in Fig. 6 by TOCS (Targets Optimizing and Constraints Softening) and DO (Dynamic Optimizer) modules. Both TOCS and DO modules solve an optimization problem, formulated taking into account the process variables prediction over a prediction horizon H_p. TOCS module solves a Linear Programming (LP) problem, characterized by the following cost function (to be minimized) and the following constraints:

$$V_{TOCS}(k) = {c_u}^T \cdot \Delta\hat{u}_{TOCS}(k) + {\rho_{y\_TOCS}}^T \cdot \varepsilon_{y\_TOCS}(k) \tag{1}$$

subject to

$$\begin{aligned} &\text{i. } lb_{du\_TOCS} \le \Delta\hat{u}_{TOCS}(k) \le ub_{du\_TOCS} \\ &\text{ii. } lb_{u\_TOCS} \le \hat{u}_{TOCS}(k) \le ub_{u\_TOCS} \\ &\text{iii. } lb_{y\_TOCS} - \gamma_{lby\_TOCS} \cdot \varepsilon_{y\_TOCS}(k) \le \hat{y}_{TOCS}(k) \le ub_{y\_TOCS} + \gamma_{uby\_TOCS} \cdot \varepsilon_{y\_TOCS}(k) \\ &\text{iv. } \varepsilon_{y\_TOCS}(k) \ge 0 \end{aligned} \tag{2}$$

DO module solves a Quadratic Programming (QP) problem, based on the following cost function (to be minimized) and the following constraints:

$$\begin{aligned} V_{DO}(k) = {} & \sum_{i=0}^{H_p-1}\|\hat{u}(k+i|k) - u_t(k+i|k)\|^2_{\mathcal{S}(i)} + \sum_{i=1}^{H_p}\|\hat{y}(k+i|k) - y_t(k+i|k)\|^2_{\mathcal{Q}(i)} + \\ & + \sum_{i=1}^{H_u}\|\Delta\hat{u}(k+M_i|k)\|^2_{\mathcal{R}(i)} + \|\varepsilon_y(k)\|^2_{\rho_y} + \sum_{j=1}^{m_b}\left\|\hat{b}_j(k+e_j|k) - lb_{b\_DO_j}\right\|^2_{T_j} + \\ & + \|\varepsilon_b(k)\|^2_{\rho_b} \end{aligned} \tag{3}$$

subject to

$$\begin{aligned} &\text{i. } lb_{du\_DO}(i) \le \Delta\hat{u}(k+M_i|k) \le ub_{du\_DO}(i), i = 1, \dots, H_u \\ &\text{ii. } lb_{u\_DO}(i) \le \hat{u}(k+M_i|k) \le ub_{u\_DO}(i), i = 1, \dots, H_u \\ &\text{iii. } lb_{y\_DO}(i) - \gamma_{lby\_DO}(i) \cdot \varepsilon_y(k) \le \hat{y}(k+i|k) \le ub_{y\_DO}(i) + \gamma_{uby\_DO}(i) \cdot \\ &\quad \varepsilon_y(k), i = 1, \dots, H_p \end{aligned} \tag{4}$$

iv. $lb_{b\_DO_j} - \gamma_{lbb\_DO_j} \cdot \varepsilon_{b_j}(k) \leq \hat{b}_j(k + e_j|k) \leq ub_{b\_DO_j} + \gamma_{ubb\_DO_j} \cdot \varepsilon_{b_j}(k), j = 1, \dots, m_b$

v. $\varepsilon_y(k) \geq 0;\ \varepsilon_b(k) \geq 0$

The main task of the DO module is the computation of H_u (control horizon) u future moves $\Delta\hat{u}(k + M_i|k)$. DO module takes into account u and y specifications and predictions ($\hat{u}(k + i|k)$, $\hat{y}(k + i|k)$) over a prediction horizon H_p (receding horizon strategy [16]). b predictions are included in order to guarantee specifications at the related furnace exit instants (e_j in (3)-(4)). The specifications related to the MVs consist in *hard* constraints (lb_{du_DO}, ub_{du_DO}, lb_{u_DO}, ub_{u_DO} in (4)) and targets ($u_t(k + i|k)$ in (3)): *hard* constraints cannot be violated since they correspond to process requirements. The specifications related to the CVs consist in *soft* constraints (lb_{y_DO}, ub_{y_DO}, lb_{b_DO}, ub_{b_DO} in (4)) and targets ($y_t(k + i|k)$, lb_{b_DO} in (3)). In *soft* constraints one slack variable for each CV has been included ($\varepsilon_y(k)$ and $\varepsilon_b(k)$ vectors) that allow temporary constraints violations. $\mathcal{S}$, Q, $\mathcal{R}$, T_j, ρ_y, ρ_b are positive semi-definite (or definite) diagonal matrices, while γ_{lby_DO}, γ_{uby_DO}, γ_{lbb_DO}, γ_{ubb_DO} are vectors composed by positive elements. The end terms of $u_t(k + i|k)$ and $y_t(k + i|k)$, together with y constraints, are provided by the upper layer steady-state module (TOCS) through the optimization problem reported in (1)-(2). The main difference between TOCS and DO modules formulation is that TOCS module does not include b specifications.

The *adaptive* mode described in this section represents the high level APC system main control mode. b status value influences the switching procedure between *adaptive* and *zones* APC modes. b status determines the inclusion of b terms in (3)-(4). When the specifications of at least one b must be taken into account, the status value of at least one b is *active* and the *adaptive* APC mode is activated (see (3)-(4) for DO formulation); otherwise (for example, in case of bad estimations of the virtual sensor), the control system switches to the *zones* APC mode [17].

Taking into account an MPC block sampling time of 30 seconds (according to the identified process model and to the furnace management), in the *adaptive* APC mode the parameters H_p, H_u and M_i are adapted taking into account the actual furnace production rate. In this way, an adaptation procedure for the horizon parameters that characterize the MPC strategy is obtained [17]. The constraints related to u have been reported in Table 2. u range values are constrained based on production type and zone temperature set points.

The developed control architecture allows reaching profitable zones temperature configurations that respect the furnace control specifications. An optimal management of the zones temperature set points allows satisfying the reheating specifications of the billets that enter the furnace. The high level APC system guarantees the optimization of all operating conditions (furnace production stage, furnace planned/unplanned downtimes). The APC system integrates the MATLAB (Mathworks) developed core software with a SCADA/HMI (Human-Machine Interface) developed on a Movicon (Progea) platform. The developed MPC formulation allows online switching on and off of each single CV. This function can be performed by plant operators through the on/off

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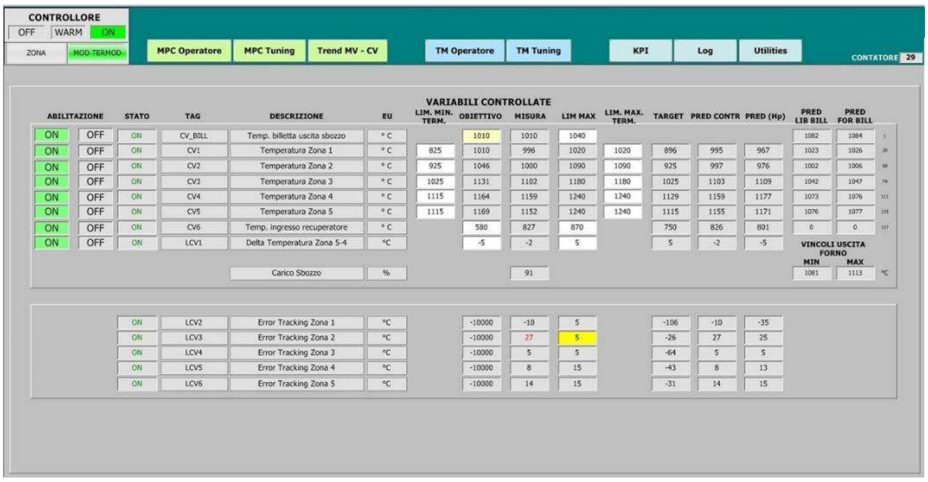

Fig. 7. HMI/GUI: CVs can be online switched on and off.

buttons reported in Fig. 7 that represents an example of the HMI/GUI developed for the APC system. In the same figure, lower and upper constraints of each CV can be noted.

4 Field Results

The high level APC system has been installed on the considered reheating furnace in April 2018. Satisfactory results with respect to the fulfillment of the billets reheating specifications have been obtained, together with energy efficiency benefits.

Fig. 8-9 represent a real process condition under the proposed high level APC system control action. The proposed scenario covers a 15 hours period, characterized by strong fluctuations of the billets inlet temperature (80 – 900 °C). The billets temperature measured by the optical pyrometer located after the first three rolling mill stands has been reported in Fig. 8 (red), together with the desired temperature target (black). The furnace zones temperature has been reported in Fig. 9. Fig. 8 shows satisfactory results for the billets temperature control: the APC system manages the fluctuation of the billets inlet temperature.

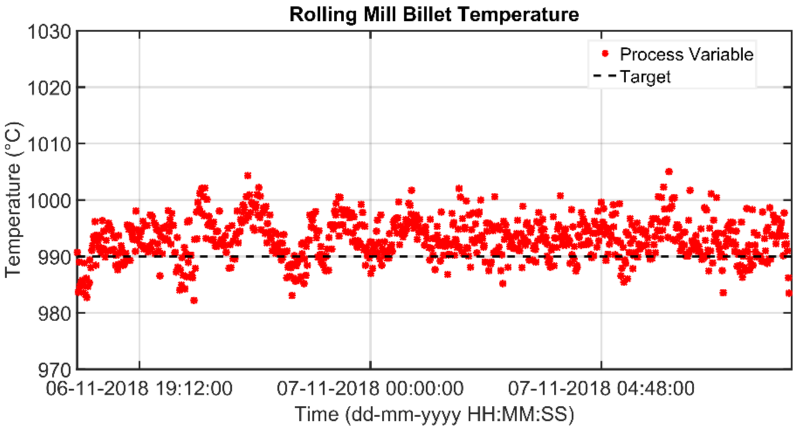

Fig. 8. Billets temperature at the rolling mill stands optical pyrometer (red) and related target (black).

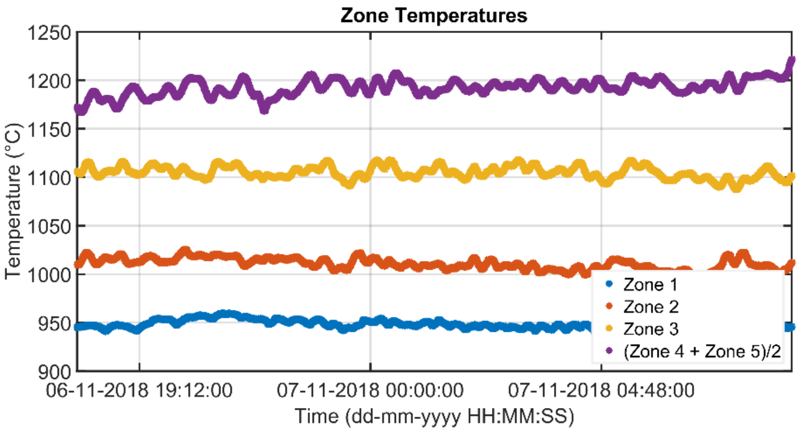

Fig. 9. Zones temperature under APC system control.

The high level APC system installation improved the reheating furnace energy efficiency with respect to the previous furnace manual conduction. The fuel specific consumption related to a significant production periods has been evaluated: a baseline has been computed, taking into account the production periods before the installation of the APC system. For the baseline computation the most significant data that have been considered are: amount of steel processed into the furnace, amount of final product, billets furnace inlet temperature, hot charge percentage and current absorption of the rolling mill stands. In this way, the not significant production periods could be discarded ("outlier") from the computation.

For example, considering the production periods related to an analyzed final product, five periods before APC system installation (Fig. 10, black) and seven periods after APC system installation (Fig. 10, blue) have been obtained. Based on the five periods

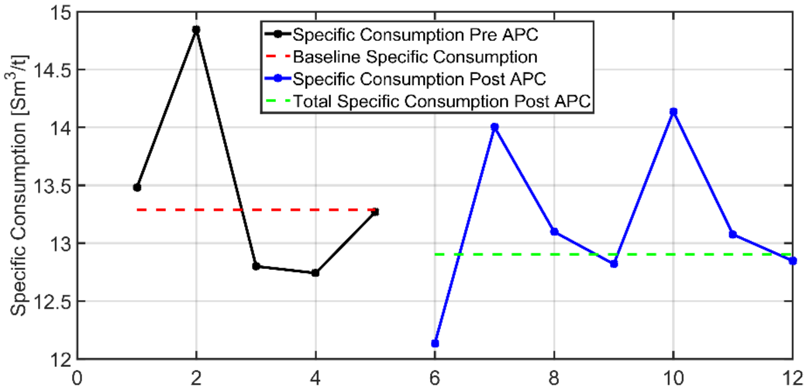

Fig. 10. Baseline analysis related to a single final product.

before APC system installation, a baseline has been computed (Fig. 10, red): the cumulative fuel specific consumption after the APC system installation (Fig. 10, green) has been decreased of 2.88% with respect to the computed baseline. This approach, based on a baseline computation, has been exploited for all production periods related to the most significant final products. In this way, a fuel specific consumption reduction around 2% has been certified.

5 Conclusions

The design and the installation of an Advanced Process Control (APC) system on a billets reheating furnace located in an Italian steel plant has been proposed in the present paper. The project has been focused on the customization of a previously patented control solution for the proposed case study. In particular, the installed APC system acts as a high level optimizer that manipulates the furnace zones temperature set points. A Model Predictive Control (MPC) strategy with an adaptive framework represents the core of the control algorithm that exploits a tailored furnace mathematical model. Some critical aspects in the steel industry reheating furnaces control, e.g. the management of the change of billets furnace inlet temperature and of the change of the furnace production rate, have been successfully addressed.

The APC system installation improved energy efficiency with respect to the previous furnace high level control, based on plant operators' manual conduction. For all production periods related to the most significant final products has been exploited a baseline approach: fuel specific consumption reduction around 2% has been certified.

Thanks to the tailored hardware and software configuration, characterized by a continuous communication between the APC system PC and the plant, the proposed control solution has been certified as Industry 4.0 compliant.

References

1. Trinks, W., Mawhinney, M. H., Shannon, R. A., Reed R. J., Garvey, J. R.: Industrial Furnaces. John Wiley & Sons, New York, USA (2004).
2. Energy Efficiency Office: Continuous steel reheating furnaces: Operation and Maintenance, Good Practice Guide 77. Harwell, Oxfordshire (1993).
3. Glinkov, M. A.: General theory of furnaces. Journal of the Iron and Steel Institute, 584-594 (1968).
4. Martensson, A.: Energy efficiency improvement by measurement and control: a case study of reheating furnaces in the steel industry. In: 14th National Industrial Energy Technology Conference. Houston, Texas, USA (1992).
5. Steinboeck, A.: Model-based Control and Optimization of a Continuous Slab Reheating Furnace. Shaker Verlag GmbH, Aachen, Germany (2011).
6. Steinboeck, A., Wild, D., Kugi, A.: Nonlinear model predictive control of a continuous slab reheating furnace. Control Engineering Practice 21(4), 495-508 (2013).
7. Steinboeck, A., Wild, D., Kugi, A.: Energy-Efficient Control of Continuous Reheating Furnaces. In: 16th IFAC Symposium on Automation in Mining, Mineral and Metal Processing, pp. 359-364 (2013).
8. Liao, Y. X., She J. H., Wu, M.: Integrated Hybrid-PSO and Fuzzy-NN Decoupling Control for Temperature of Reheating Furnace. IEEE Transactions on Industrial Electronics 56(7), 2704-2714 (2009).
9. Yi, Z., Su, Z., Li, G., Yang, Q., Zhang, W.: Development of a double model slab tracking control system for the continuous reheating furnace. International Journal of Heat and Mass Transfer 113, 861-874 (2017).
10. Santos, H.S.O., Almeida, P. E. M., Cardoso, R. T. N.: Fuel Costs Minimization on a Steel Billet Reheating Furnace Using Genetic Algorithms. Modelling and Simulation in Engineering 2017, Article ID 2731902, 11 pages (2017).
11. Hu, Y., Tan, C. K., Broughton, J., Roach, P. A., Varga, L.: Model-based multi-objective optimisation of reheating furnace .operations using genetic algorithm. Energy Procedia 142, 2143-2151 (2017).
12. Astolfi, G., Barboni, L., Cocchioni, F., Pepe, C., Zanoli, S. M.: Optimization of a pusher type reheating furnace: an adaptive Model Predictive Control approach. In: 6th International Symposium on Advanced Control of Industrial Processes, pp. 19-24 (2017).
13. Astolfi, G., Barboni, L., Cocchioni, F., Pepe, C.: Metodo per il controllo di forni di riscaldo. Italian Patent n. 0001424136 awarded by Ufficio Italiano Brevetti e Marchi, 2016.
14. Zanoli, S. M., Pepe, C., Barboni, L.: Application of Advanced Process Control techniques to a pusher type reheating furnace. Journal of Physics: Conference Series 659(1) (2015).
15. Zanoli, S. M., Pepe, C.: Two-Layer Linear MPC Approach Aimed at Walking Beam Billets Reheating Furnace Optimization. Journal of Control Science and Engineering 2017, Article ID 5401616, 15 pages (2017).
16. Maciejowski, J.: Predictive Control with Constraints. Prentice-Hall, Harlow, UK (2002).
17. Zanoli, S. M., Cocchioni, F., Pepe, C.: Model Predictive Control with horizons online adaptation: a steel industry case study. In: 2018 European Control Conference, pp. 2332-2337 (2018).