Effect of Cascade Tuning on Control Loop Performance Assessment

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Abstract: The effect of cascade tuning on control loop performance is analyzed in the framework of a monitoring system implemented in a refinery plant. Improper (too conservative) tuning of the inner loop may bring to ambiguous or apparently wrong verdicts on the evaluation of single loop performance. Starting from the evidence that operators actions can be different from suggestions given by the monitoring system, the effect of cascade controllers tuning is examined through the illustration of possible scenarios, generated in simulation with different tuning policies. Explanation of the observed behavior and general guidelines to assist operators in the procedure of controller retuning are given.

Keywords: Process Control, Performance Monitoring, Controller Retuning, Cascade control

1. INTRODUCTION

Beneficial effects of cascade in allowing more efficient suppression of perturbations affecting the process are known since the early era of process control. Referring to the scheme reported in Figure 1 (for the more common series cascade), every time it is possible to have measurements of process internal variables (PV_i), a faster suppression of the disturbance on the controlled variable (PV_e) can be obtained, with respect to a single feedback controller, by the two controllers: the primary (C_e), acting in cascade on the secondary (C_i),

Advantages of cascade control increase with speed of the inner loop with respect to the outer one; in industrial applications a large number of Flow Control (FC) are inner loops (slave) of cascade control scheme, being faster than outer loops, for instance Pressure or Level Control, which act as master controllers.

Design of cascade controllers can be found in textbooks (for instance: Visioli, 2006). Usually it is performed by first tuning the secondary controller C_i based on P_i and then tuning the primary C_e based on the closed loop transfer function of the inner loop in series with the outer one: $P^*=P_eP_iC_i/(1+PiC_i)$. In the case of tight tuning of C_i, P^* reduces to P_e. Very often C_i is Proportional, leaving the Integral action to C_e, as an offset free response is required only on PV_e.

Autotuning of cascade controllers has also been proposed referring to the standard relay feedback approach; the application can be sequential (Hang et al., 1994) or simultaneous (Tan et al., 2000), being the second less time consuming. A comparison of different approaches to autotuning of cascade controls is reported in Leva and Marinelli (2009).

As common practice in the industry, a trial and error approach to controller tuning is taken, even though it is evident that a correct tuning of both controllers is important to obtain good performance on loop variables. It is also known that control operators tend to detune controllers in order to avoid oscillations in loop variables. In the paper the effect of a conservative tuning of cascade controllers is analysed in the framework of a closed loop performance monitoring system operating on refinery plants.

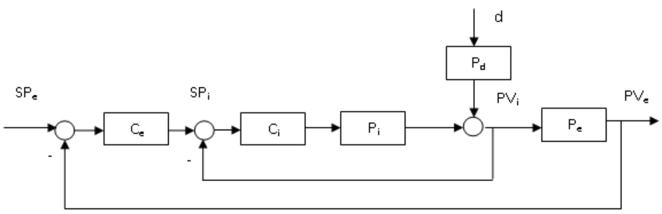

Fig.1: Scheme of a (series) cascade control loop

The paper has the following structure: section 2 presents the architecture of the monitoring system and main features of analysis modules; section 3 illustrates the problem of cascade tuning met in the industrial application with an analysis of different solutions; section 4 reports some conclusions and general guidelines about retuning of cascade controllers.

2. THE PERFORMANCE MONITORING SYSTEM

2.1 The Loop Control Architecture

A general illustration of the system (denominated *Loop Control*) and analysis of results are reported in Scali et al. (2009) and in Scali and Farnesi (2010). A synthetic picture of the system architecture is depicted in Figure 2, where different modules and their interconnection are indicated.

The User Module (MU) starts the whole procedure by sending a message to the module of scheduling (MS) about the sequence of plants (and loops) to be analysed (the procedure is repeated periodically). In addition, it allows to see the state of advancement of operations, to display results and to send specific queries to the database (DB). The user module also permits the configuration of the loops which is the very first step of the performance monitoring process. Loops configuration consists in the assignment of loop name, DCS address, loop info (for instance: single loop or cascade), priorities and constraints of the acquisition. More important loops can have higher frequency of acquisition, cascade loops are acquired simultaneously, loops of the same process unit are analysed in the same data acquisition run.

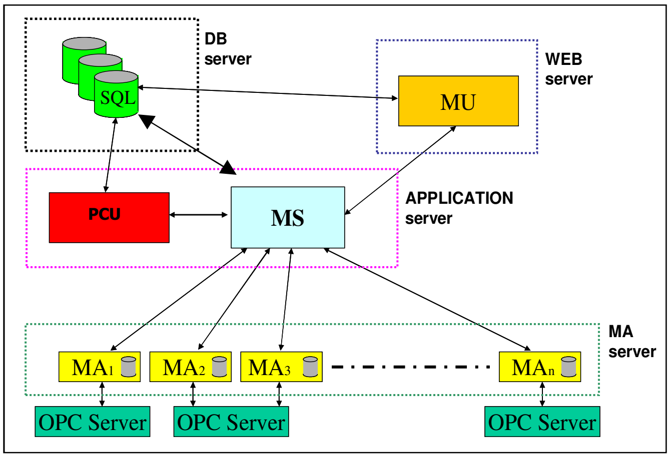

Fig.2: The system architecture

<u>The Scheduling Module (MS)</u>, once activated by MU, sends a command to acquisition modules (MA_i) which perform physically the acquisition of data from the DCS. For each loop, specific information is transferred to the Data Base (DB) trough MS, such as: loop tag name, controller settings, ranges of controlled variable (PV) and controller output (OP), saturation limits, loop hierarchy (e.g. master/slave of a cascade loop, loops under advanced control). Also information about default, minimum and maximum values for the duration of acquisition and sampling time (ts) is exchanged (by default, ts= 10 seconds). Once acquisition is terminated, MS receives from MA_i data files which are sent to the DB input section. It activates the performance analysis accomplished sequentially by the PCU (Plant Check Up) module; finally, verdicts about loop status generated by PCU are transferred to the output section of the DB.

<u>Acquisition Modules (MAi)</u> interact with DCS, from which receive data and loop parameters value at each sampling time; they act in parallel (up to a maximum number of 7 on a single server) and sequentially on scheduled loops, following priority and constraints indicated by MS. During the acquisition, the quality of each single datum and the change of status (man/auto, cascade open/closed) is checked and a flag is activated. In addition a first analysis is performed locally: mainly, the duration may be increased from the default (2 hours) to the maximum value (8 hours) in order to get a significant number of cycles in the case of very slow oscillating loops.

2.2 The PCU Module

The PCU module is the engine of the performance monitoring systems: it analyses each loop sequentially, interacting with the MS and with the DB from which receives raw data and to which send verdicts. A schematic representation is reported in Figure 3, where main steps and a simplified logical flow of data analysis modules are indicated. Main modules are illustrated below.

IM: The <u>Initialization Module</u> imports parameters values from file IN1 and performs a first check about loop status; if the quality of data is not good, or a change of configuration is detected, or the valve is operating manually (info contained in flags activated by MA_i), the analysis stops. In this case, the loop receives a (definitive) label (NA: Not Analyzed) and the analysis is aborted. Otherwise, recorded data are imported from the IN2 file and the performance analysis begins.

AIM: The <u>Anomaly Identification Module</u> performs a first assignment of performance, issuing verdicts as: G (*Good*), NG (*Not Good*). Loops subject to excessive set point changes (as amplitude or frequency) are temporary labelled as NC (*Not Classified*) and send to the identification module (I&RM). Valve saturation is checked first and, if detected, the label NG (and the cause) is definitive, without any further analysis (only duration is indicated). For loops not in saturation, after a data pre-treatment, tests to detect oscillating or sluggish loops are executed; these tests refer to the Hägglund approach (Hägglund, 1995, 1999), with suitable modifications of internal parameters, based on field calibration. In the case of both negative tests, the loop is classified as good performing and a definitive label G is assigned. Slow loops can only be caused by the controller: therefore they receive a NG label and are sent to the identification and Retuning Module (I&RM). Oscillating loops can be caused by aggressive tuning, external disturbance or valve stiction: for this reason, they are primarily sent to FAM, for a frequency analysis.

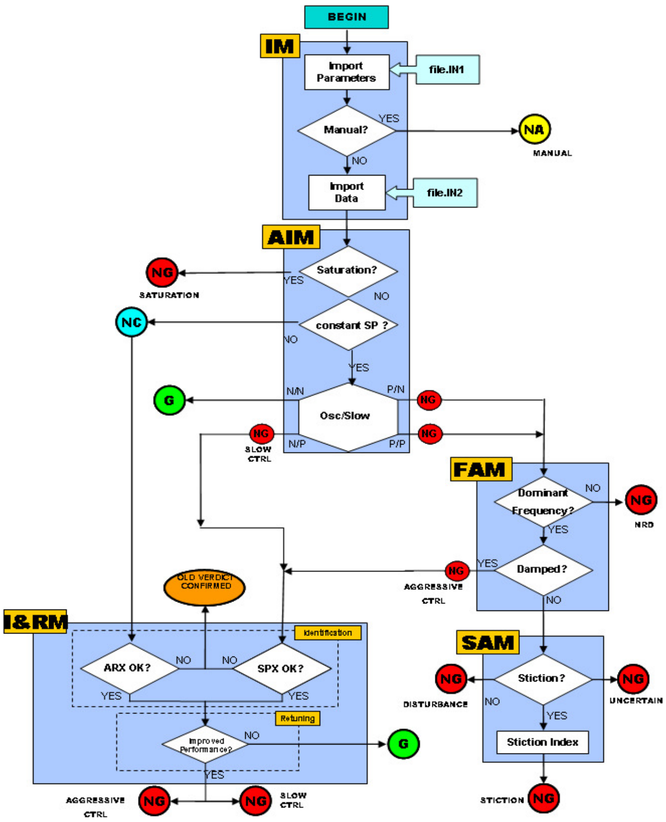

Fig.3: Schematic representation of the PCU module

FAM: The <u>Frequency Analysis Module</u> has the scope of separating irregular oscillations from regular ones on the basis of a power spectrum which computes dominant frequencies; irregular loops are labelled NG, without any further enquiring about causes. Regular loops with decaying oscillations are sent to the I&R Module, otherwise (i.e. loops showing permanent oscillations) to the SAM for stiction/disturbance detection.

SAM: The Stiction Analysis Module analyzes data of NG oscillating loops and performs different tests to detect the presence of valve stiction. They mainly consist in the application of two techniques: the Relay based fitting of values of the controlled variable (PV) (Rossi and Scali, 2005) and the improved qualitative shape analysis (Yamashita, 2006; Scali and Ghelardoni, 2008). Other techniques proposed for stiction diagnosis are also applied, when appropriate: the Cross-Correlation (Horch, 1999) and the Bichoerence (Choudhury et al. 2005). At the end, in the cases of strong evidence, the cause *Stiction* or *Disturbance* is assigned to the loop under analysis (already tagged NG), otherwise the cause remains *Uncertain*.

I&RM: The Identification & Retuning Module accomplishes process identification and, if successful, controller retuning and evaluation of performance improvements. It analyses loops tagged NG, owing to controller tuning (that is sluggish or too oscillating responses) and loops tagged NC. The two possibilities of constant and variable Set Point are treated differently. In the case of constant SP (typical of the master cascade controller), recorded data represent a loop response under disturbance rejection: identification of process dynamics is carried out by means of a Simplex based search procedure (Scali and Rossi, 2009). In the case of variable SP, (typical of the slave cascade controller), recorded data represent a loop response under set point tracking: identification is performed by means of an ARX algorithm (Ljung, 1999). In both cases, if model identification is successful, new tuning parameters are calculated according to different techniques, the achievable performance improvement is evaluated by means of suitable upgrading indices and new controller settings are proposed. Otherwise, in the case of impossible identification, the previous assigned verdict is confirmed, without any additional suggestion about causes.

Therefore, after the performance analysis by means of the PCU module, every loop is classified as:

- NA (Not Analysed): Manual valve, invalid data acquisition, change of loop configuration;

- NC: (Not Classified): impossible identification and no preliminary verdict;

- G (Good Performing);

- NG (Not Good performing): with an indication of cause (*saturation*, *sluggish, too oscillating, stiction, external disturbance*), or without indication (irregular disturbances or uncertainty between stiction and disturbance in the SAM).

To conclude this synthetic illustration, the monitoring system has been designed to operate completely unattended: verdicts and causes are assigned only in case of strong evidence, to avoid wrong verdicts. Nevertheless, verdicts are issued as a consequence of threshold values assigned in the configuration stage by interaction with plant operators, therefore they depend on initial calibration.

The effect of threshold values for the widely used Hägglund criterion (1995) and a comparison with similar criteria to classify the loop as oscillating, are reported in Scali et al. (2010).

There, the point was to reduce the number of NG verdicts issued by the monitoring system for loops having a performance considered as acceptable by plant operator common practice and then felt as a sort False Alarms. Here, the focus is on performance assessment of cascade control loops and their tuning, comparing the indication of the monitoring system with the action performed by operators.

3. THE CASCADE TUNING PROBLEM

3.1 Modeling the observed situation

In several cases the PCU verdict classified the outer loop as "Good" and the inner loop as "Slow": so the suggested action was to increase the gain of the slave controller. The operator preferred to decrease the gain of the master controller and this was motivated by the fact that the controlled variable did not get worse (or showed a little improvement), while the main achieved benefit was in reducing the variability of the internal variable and then valve oscillations.

The situation is reported in Figure 4, showing trends of loop variables before and after operators intervention. It is evident that after master detuning both oscillation amplitudes decrease.

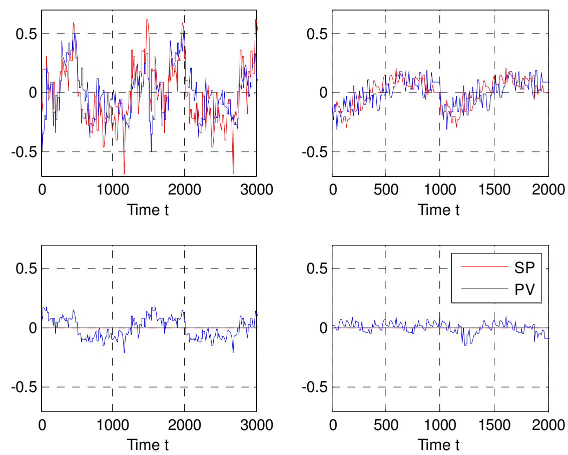

Fig.4: Trends of master (bottom) and slave (top) variables (red: SP, blu: PV); before (left) and after (right) master detuning

As this action was against the expected logical (at the end both loops are detuned), the whole situation of cascade tuning was re-analyzed to explain the validity of the operation and to find a general approach to suggest actions to be performed on cascade loops.

Referring to Figure 1, inner and outer process (P_i and P_e) are assumed as First Order Plus Time Delay dynamics, with the inner process (typically a Flow Control) much faster than the outer. PV_i, PV_e, SP_i, SP_e indicate controlled variables and Set Point of the two loops. The perturbation is a periodical signal (for simplicity of sinusoidal type), which can have different dynamics according to the inlet point. Both controller are Proportional Integral, with tuning according to the Ziegler and Nichols rule; C_i is based on P_i, C_e on P*. Assumed values of parameters and expressions for the two closed loop functions PV_e and SP_i are reported below. Assumptions about design techniques and process parameters should not be seen as limitative of the validity of the study, oriented to explain different approaches to improve cascade control performance.

$$P_j(s) = \frac{e^{-\vartheta_j s}}{\tau_j s + 1}, C_j(s) = Kc_j \frac{\tau i_j s + 1}{\tau i_j s}, j = i, e, P_d = 1$$

$$\theta_i = \tau_i = 5, \theta_e = \tau_e = 10; Kc_i = Kc_e = 1; \tau i_i = 13, \tau i_e = 40$$

$$\frac{PV_e}{d} = \varepsilon = \frac{P_e}{1+P_i C_i (1+P_e C_e)}, \frac{SP_i}{d} = -C_e\, \varepsilon$$

3.2 Effect of controllers tuning

As first, the effect of master and slave controller gain on loop performance was examined. A change in the gain K_c with respect to the nominal tuning of a factor F=1.5 for increase and of a factor F=5 for decrease, was introduced. Results are reported in Figure 5, where the modulus of the sensitivity function ($\varepsilon = PV_e/d$) is plotted as a function of the frequency ω.

In Figure 5, the typical response of feedback control is shown: at very low frequency ($\omega \to 0$) the integral action allows almost perfect disturbance suppression; the same happens at very high frequency ($\omega \to \infty$), as a consequence of the process capacity in attenuating disturbance. In the intermediate frequency range (around the ultimate frequency of the system $\omega_u \approx 0.1$), a desired attenuation of the oscillation may not be reached, because all the ε curves reaches 1.

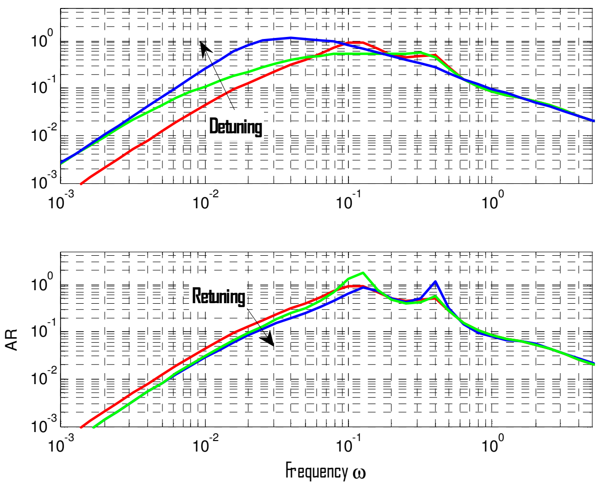

Fig.5: Effect of controller tuning on disturbance suppression; correct tuning (red); master (green); slave (blu)

About relative merits of controller actions, the effect of an increase of gain is very similar in the low and high frequency range. Some differences can be observed in the middle frequency range in terms of maximum value and frequency value where it occurs; in particular detuning the slave loop causes a larger increase in PV_e oscillation amplitude.

3.3 Detuning the secondary loop

In the industrial cases, the verdict of the monitoring system about controllers tuning indicated: correct master, slow slave; to reproduce this case in simulation the slave controller gain was reduced (Kc_i=0.1). As recalled, the operator action (master detuning) was motivated also by the need of decreasing the variability of slave loop variables. In addition to the controlled variable (PV_e/d), also the inner loop required Set Point (SP_i/d) has been analysed. Results are reported in Figure 6 (observed case means detuned slave loop).

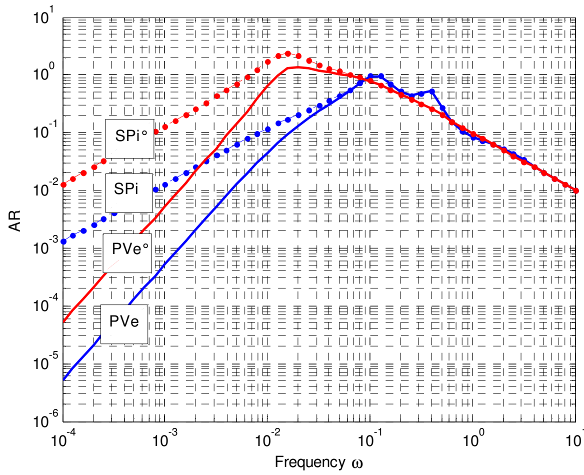

Fig.6: PV_e and SP_i trends: observed case [°] vs. correct tuning

By analyzing trends in Figure 6 it is evident that the effect of an incorrect tuning of the slave controller causes a decrease of the frequency range where the disturbance can be satisfactorily suppressed: PVe reaches 1 at a much lower frequency ($\omega \approx 0.015$, instead of $\omega \approx 0.1$).

Also, a detuning causes an increase of the required Set Point variation in the inner loop (SPi), which reaches much larger values at constant frequency; (for instance, at $\omega \approx 0.015$, with correct tuning: PV_e=0.1, SP_i=0.18; at the same frequency, in the observed case: PV_e=1.3, SP_i=2.4); the same happens at constant disturbance attenuation.

Therefore, a correct tuning seems to allow better results in terms of reducing PV_e and SP_i variations in all the frequency range of interest.

3.4 Detuning the primary loop

Now the effect of a decrease (F=10) of the master controller gain has been analysed, assuming that the observed industrial situation is reproduced by the simulated case (master-correct and slave-slow tuning) previously illustrated; results are reported in Figure 7.

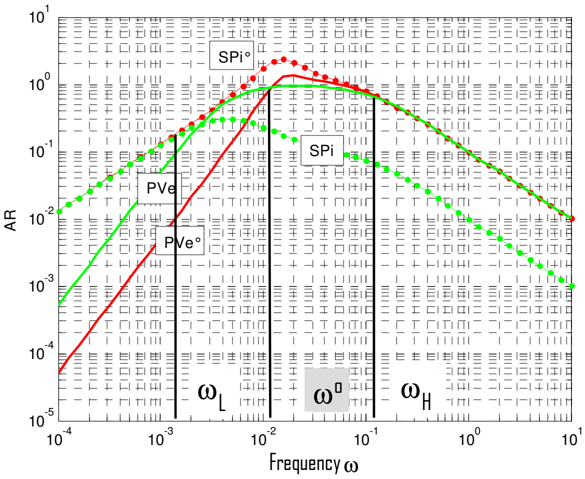

Fig.7: PV_e and SP_i trends: master detuning vs. observed case [°]

Now the effect is different on PV_e and on SP_i and it is appropriate to distinguish between low and high frequency. In the following considerations, to improve means to reduce the amplitude of the oscillation, while to worsen means to increase it.

In the low frequency range ($\omega<\omega_L$), a detuning of the master controller has no effect on SP_i, while PV_e worsens. At intermediate frequencies, up to $\omega<\omega°$ (intersection between PV_e and $PV_e°$), improves SP_i but PV_e worsens, while for $\omega>\omega°$ improves both SP_i and PV_e. For higher frequencies ($\omega>\omega_H$), SP_i is improved, at constant PV_e.

3.5 Comparison between the two different actions

For a better evaluation of the validity of master detuning with respect to slave retuning (the second being suggested by the monitoring system), trends of PV_e and SP_i, shown in Figures 6 and 7, are compared and both reported in Figure 8 for ease of comparison.

At low frequency, master detuning makes PV_e slightly worse (still acceptable) and does not act on SP_i; slave retuning improves both PV_e and SP_i; (for instance: at $\omega\approx0.004$ rad/s, PV_e amplitude decreases from 0.1 to 0.01 and SP_i from 0.7 to 0.07).

In the intermediate frequency range one action or the other may be more convenient, according to the priority given to PV_e or SP_i attenuation. As priority is given to SP_i (once PV_e is considered acceptable), it can be seen that master detuning can be favorable for $\omega>\omega^*$ (being ω^* the frequency where the two SP_i curves cross); for instance: at $\omega=\omega^*$, while PV_e does not change too much (from 1.4 to 0.9), the effect on SP_i is much larger (from 2.3 to 0.2).

In the high frequency range both actions have no effects on PV_e; again, master detuning attenuate SP_i oscillation; for instance: at $\omega\approx1$ rad/s, while PV_e does not vary (PV_e=0.1), SP_i is attenuated from 0.1 to 0.01.

Therefore, advantages of a correct tuning in the two loops in terms of global loop performance (i.e. on PV_e attenuation) in the frequency range of interest are evident; in the case that the amplitude of PV_e oscillation is considered acceptable by the operator, a master controller detuning can be considered more efficient in reducing the variability of the inner loop SP_i in the middle-high frequency range ($\omega>\omega^*$).

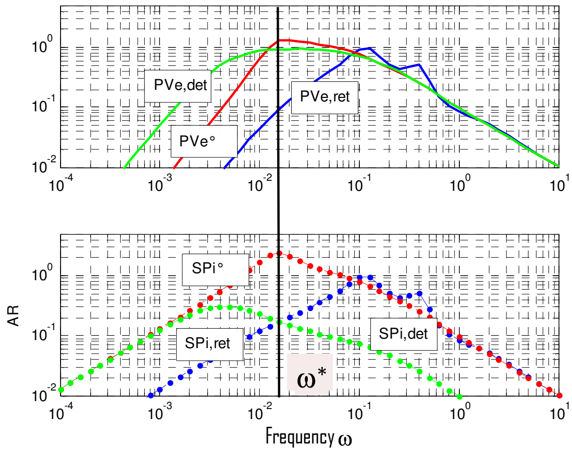

Fig.8: PV_e and SP_i trends: master detuning and slave retuning vs. observed case [°]

3.6 Further considerations

The situation for the case of single Feedback Control (no cascade) can be recalled for a further understanding. Trends of the controlled variable (PV) and of the required control action (OP, which substitutes SP_i) for the two cases of correct and aggressive tuning of the Feedback controller (C), are reported in Figure 9.

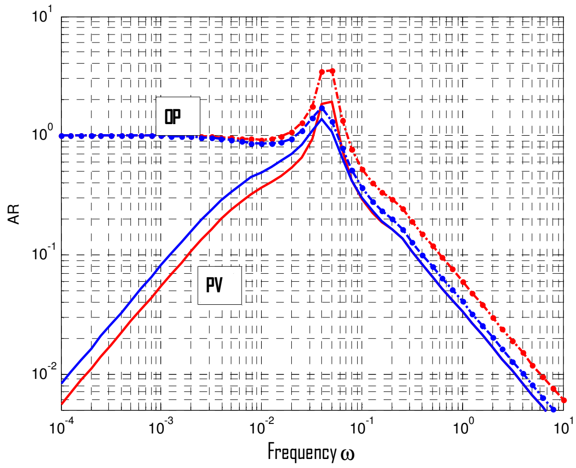

Fig.9: FB Control (no cascade): effects of correct (blu) and aggressive (red) tuning on PV(-) and OP (-.-)

PV trend is analogous with and without cascade: good attenuation is achieved in the low and high frequency range, while no disturbance attenuation is possible in the intermediate range. The main difference regards OP trends: at low frequency an attenuation of the oscillation amplitude of the required control action (OP) is not possible, while this can be done in the middle-high frequency range ($\omega\geq\omega_u$), without affecting PV amplitude. The familiarity with this situation can be seen as a suggestion for the choice of master detuning in the discussed industrial case.

Choice of the correct action can be done only on the basis of a knowledge of process and controller parameters and after performing an analysis of loop functions, which would allow to evaluate the ω* frequency. Otherwise the master detuning can be adopted only for perturbations at frequencies higher than the ultimate frequency of the system.

In the case of cascade control different ultimate frequencies (ω_u) of the system can be defined, accounting for the effect of control structures and tuning. In Figure 10 trends of phase (Φ) as function of the frequency are reported for different cases (ω_u: $\Phi(\omega_u) = -\pi$); it can be observed that the ultimate frequency of the open loop process ($P=P_i*P_e$) is the largest one: this value, at least, is required.

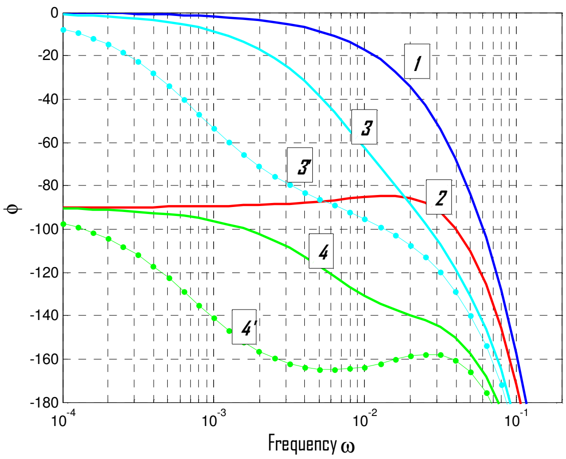

Fig.10: Phase trends (Φ) as function of the frequency ω in the 4 cases: (1): OL process $P=P_i*P_e$; (2): Feedback OL function: G=P*C; (3): Inner Process with cascade active: $Z=P_i*C_i/(1+P_i*C_i)$; (4): cascade OL function: Y=Z*Ce. (Case 3' and 4': increased gain in the inner loop)

4. CONCLUSIONS

The analysis illustrated above allows a full understanding of effects of cascade controllers tuning on loop performance and to find an explanation to operator detuning of master loop while the monitoring system suggested to retune the slave loop. In the case that basic assumptions of the study (values of process parameters, Ziegler-Nichols tuning of the two (PI-type) controllers) are changed, some different scenarios may appear, but general conclusions do not change that much.

Assuming as performance criterion the attenuation of the perturbation on the output controlled variable (PVe), no doubts about the superiority of a correct tuning of the two loops in all the frequency range. No possibility of improving performance in the very high frequency range, where in any case the perturbation is attenuated.

In the case that the performance criterion includes also the reduction of the variability of the inner loop variables and the amplitude of oscillation in the controlled variable is considered acceptable by the operator, a master controller detuning can be considered more efficient in the middle-high frequency range. Controller detuning is the only action which can be performed in the case of feedback control.

The optimal action requires a knowledge of process and controller parameters and an analysis of loop functions to evaluate the frequency value (ω*) to discriminate. Limiting this knowledge to the ultimate frequency of the open loop process (ω_u), the master detuning should be adopted only for perturbations at higher frequency ($\omega > \omega_u$).

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