

# An Integrated Environment for Industrial Control Performance Assessment, Diagnosis and Improvement

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**Abstract** — The last 15 years have been very tough for the Industrial Process community. The continuous process industry has had to cope with the need to recover any possible production edge maximizing production rates, quality yields, utilities consumption savings and overall equipment service factor. Consequently any piece of the production process has been revised and assessed in the quest for any possible contribution to the overall “operation optimization”. In this perspective automation has been promoted from a pure unavoidable (but dull) “technology tool” to the role of real production asset, whose performances must be duly monitored, maintained and, where possible, improved.

However, the simultaneous dramatic reduction in engineering staff process industries have experienced in the last 15 years, has actually prevented that profit-oriented corporate rules and recommendations could be transformed in effective strategies and best practices.

The present paper presents an innovative computer-aided procedure that has been designed to help properly addressing, prioritizing and solving some of the most challenging problems which have heavy impact on maintenance and control engineers’ everyday operation.

The procedure is based on a clever combination of top-down and bottom-up approaches aiming at maximizing the exploitation of information included into available process data, so minimizing both the initial investment and human interactions.

The innovative software package, featuring novel algorithmic and result visualization techniques, will be described together with a relevant case study.

## I. INTRODUCTION

*“Without properly tuned control loops to minimize variability, and updated process models used by the advanced controls to reflect real constraints and business objectives, substantial benefits are lost”*. This quote from a recent editorial from the Hydrocarbon Processing Journal [1] underlines effectively what most continuous processes have realized: neglecting control loops performances have a clear, visible effect on process economics and profitability.

Control loops are an intrinsic part of any automation system. A control loop is a significant investment, larger than what could be thought at first (see [2] for an analysis of control loop economic value). Taking into consideration hardware components (sensors, actuators, the share part of the electronics and cabinets), software (the share part of the DCS licenses) and manpower (installation & erection, commissioning and tuning) it is not difficult to realize that each control loop should be

considered as a multi thousand Euro asset for each and every continuous process plant.

Consequently, taking care and maximizing the return of investment of control loops becomes an integral part of that set of operational excellence initiatives which goes under the very fashionable (even if not always fully understood) term of Asset Management ([3], [4]).

Control Loop Condition Monitoring (CLCM) is as significant as the condition monitoring of equipment, valves and transmitters. In any control application, basic control loops always have the same principle of operation – no matter what the current application deals with. This feature facilitates the establishment of common practices for control loop condition monitoring applicable in different industries.

For the practitioner, a basic control loop typically looks as in Figure 1.

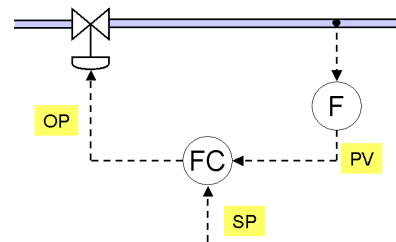


Figure 1 - Typical flow control loop diagram as from P&ID

A final control element (e.g. a valve) is used to keep a certain variable (e.g. the actual product flow) close to a target, provided by either the operator or by a higher level component in the automation pyramid (e.g. a multivariable controller). This task should be done autonomously, no matter what kind of disturbances upsets the process during operation.

Over 90% of the process control systems are based on PID type controllers, which represent a standard as regards process tuning. These controllers, the basic principle of which is fairly simple, are the basis of any automation strategy, even when advanced, second-layer systems, like multivariable controllers are applied.

As time goes by, however, changes in production conditions or normal settling of component parts, sensors and actuators can affect the effectiveness of regulation. These changes can vary from changes in process gain or dynamics, to valve operation problems (stiction<sup>1</sup>, hysteresis) to the enforcement of new constraints on operating conditions. Moving away from original tuning

<sup>1</sup> The term *Stiction* (short term for Static Friction) identifies all those events due to friction on the valves

conditions would therefore call for the periodical retuning of the controllers, so as to adapt tuning to changes in operating conditions<sup>2</sup>.

Automatic condition monitoring of control loops is of interest because in most plants, the number of control loops per service engineer is usually so large that a manual maintenance is simply unsustainable. The half-time of good performance is six months, i.e. a control loop performance needs to be assessed at least once-twice a year.

Assuming that an expert engineer takes between two to four hours to check and re-tune a control loop and that he is responsible for 500 loops, this would result in an effort of approximately ten man-months (per year) of pure tuning activities. It is evident that tool support is required to focus activities on the really significant and crucial loops (usually a smaller subset).

A further contribution to the problem comes from the fact that manually tuning 3-degrees of freedom controllers, like PIDs are, is not a task for everyone. Usually it takes a lot of experience and judgement, exactly what is running short at many plants where fewer new engineers have been hired to substitute retired ones and have to manage a wider range of tasks.

Practically, the decision not to maintain actual basic control tuning is forced because of:

- Shortage of manpower
- Shortage of expert resources

This situation is by no mean exclusive to process control. Similar problems have been overcome in other industrial sectors relying on software tools able to raise both productivity and skills of smaller crews.

From a technical perspective situation is challenging as well. In order to be really effective, Control Loop Condition Monitoring must be inherently passive and non-invasive. The major requirement is that no more information than the usually available one can be used for analysis: by passively listening to the process, a diagnosis has to be established.

While, in the design phase, the designer usually specifies a controller that satisfies some given performance specifications, the situation is different for CLCM where no ad-hoc experiment is practically possible.

Figure 2 compares two different tuning sets for the same loop: whereas it is easy to tell which the best is at the design stage, the same is not so easy just looking at historical trends.

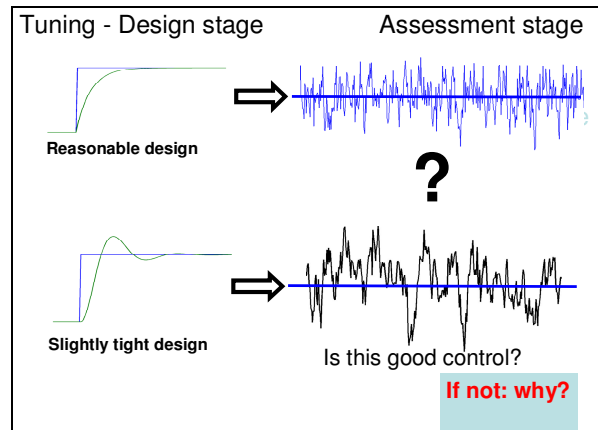


Figure 2 - Performance Assessment: Tuning vs. Auditing

It was the celebrated paper of Harris [5] that initiated a considerable research activity in both academia and industry. In [5], a simple and very appealing performance measure was defined that could be evaluated for any control loop under normal operating conditions. The Harris index focused on quantification of the avoidable part of the control error variance. It allowed comparing the current controller performance to the theoretically best achievable one by simply stating the factor by which current variability is too high compared to the optimal one (the Minimum Variance Controller – MVC).

During the last ten years, considerable efforts have been spent to build a passive methodology able to assess controller performance automatically. Notwithstanding research activity is still ongoing and required for some open questions (for a recent overview of ongoing research, see [6]), specific software packages are now commercially available.

Industry users and experts have accurately identified the actual requirements for a valid data-driven disturbance analysis toolkit. As a significant example, the valuable and concise prerequisite list provided in [7], is reported below:

- Turn data into concise targeted information
- Streamline and reduce troubleshooting time
- Yield information to enhance maintenance efforts during plant shut-down
- Discover problems not found with traditional “fight today’s fire” approaches

## II LOOP PERFORMANCE MANAGER DESCRIPTION

Optimize<sup>IT</sup> Loop Performance Manager (since now indicated with the acronym LPM) is a process control maintenance tool for control engineers, instrument technicians and maintenance personnel, which has been designed to provide a bridge between the technologies developed in the academia and the existing, relevant needs in the industrial world [8]. Its mission is to ensure that control loops, and – consequently – the whole production process, operate at peak performance.

The package is structured in three independent modules:

<sup>2</sup> It should be noted that this type of problem can in some cases be completely inherent in the specific type of production and not relate to the history of the unit and *equipment*. This is the case of plants working with *campaign productions* (typical in the fine chemicals industry) where the load conditions and the type of product can vary from one period to another, leading to the need for specialized tuning for the different production campaigns.

- 1) a tuning component used to improve control loop performance,
- 2) an auditing component used to monitor loop performance
- 3) An additional software component able to analyze simultaneously multiple loops detecting common behaviors and identifying possible root causes, thanks to novel algorithms. For its capability to correlate causes and effects all over the whole process topology, this element goes under the name of Plant-wide Disturbance Analysis (PDA).

Depending on customer needs and constraints any combination of the three modules could be installed and applied, allowing for maximum flexibility.

#### A. Tuning

As seen above many plants (actually the majority) forgo potential economic benefits from their distributed control system (DCS) investments, because of poorly tuned or manually operated loops.

LPM provides a powerful, yet extremely easy-to-use, environment for computer-aided loop tuning. The package supports tuning for a wide variety of commercial PID controllers, as well as various configuration options for the PID control algorithms. By combining data collection, modeling, tuning and simulation in a single user interface, it helps to remove the barriers preventing optimization of DCS investments.

The model-based tuning procedure permits to explore different controller set-ups whose objective and measurable performances can be compared and assessed (both graphically and numerically) through an embedded off-line simulator. Integrating processes (i.e. levels); feedforward and cascade loops are all manageable by the software.

When the tuning is completed the user can append all the tuning results and performances to a loop-specific log file, that – as time goes by - will become a kind of logbook containing all the maintenance activities. Storing not just the tuning constants, but all the details related to the whole tuning process (from data file, to model details and performances to tuning methods and results) it will preserve for future reference or even for the future generations the gained operation expertise, avoiding to dissolve it when relevant personnel is moved to different positions.

#### B. Auditing description

Once loops are well tuned, the objective is to maintain them at the optimum performance: as seen, in the traditional approach an expert engineer should (ideally) spend most of his/her time looking at hundreds of signals/trends and from these detects system problems. LPM Loop Auditing does this automatically, processing just the 3 main loop signals available in any DCS (highlighted in Figure 1) and routinely assessing operation and detecting possible problems.

Figure 3 describes schematically how Auditing works. An embedded, configurable scheduler allows LPM to

collect live data over a standard OPC connection at multiple, pre-defined times during the day. For each loop 3 signals are collected: (Process Variable, Setpoint and Control Output). It should be noted that the “data collection batches” permit to satisfy two conflicting requirements:

- Assess loop performances “almost” continuously
- Not overload the acquisition channels.

After data collection is complete, up to 50 different performance indices are computed and stored in the auditing database. Of these 3 (% of time in auto mode, % of time in saturation, absolute mean error) are calculated in continuous mode as a statistic reference. The others are devoted to analyze several possible aspects of the signals like data validity, tuning performance, oscillation and non-linearity features and valve health behavior.

With the addition of a proper knowledge base the indices are on their turn, processed to compute diagnostic hypothesis, which are expressed as clear maintenance indications like “*Tuning Problem*”, “*Loop Oscillatory*”, “*Valve Stiction*”, etc.

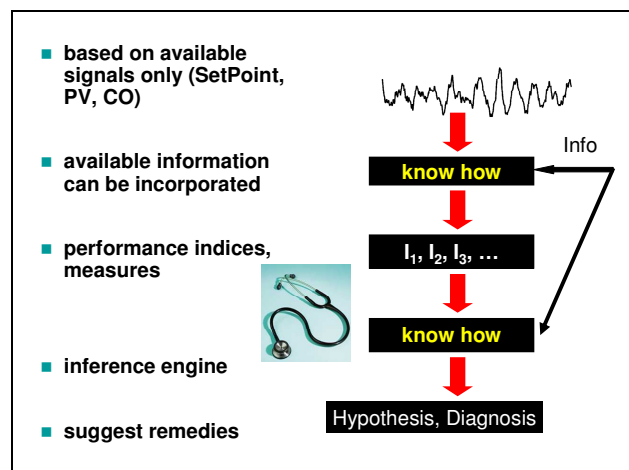


Figure 3 – LPM Auditing Concept

Once a week a configurable report (available in both HTML and spreadsheet formats) is automatically generated and saved, allowing the maintenance crew to access the needed information when more convenient. All these actions are executed routinely in background: once configured, Loop Auditing does not need any human interactions. Plant engineers have only to periodically examine the report generated by LPM with the status of the process and control system.

Figure 4 shows some of the different types of reports available in LPM. Results are organized hierarchically to facilitate access and quick identification of critical information. At the highest level, loops are categorized in four classes (from EXCELLENT down to POOR) following an eye-catching color-code. More details are provided both as quantitative (in the form of performance indices) and qualitative information (diagnosis). The qualitative information comes from the evaluation of statistical rules against the calculated performance indices. Using the collected data, the user can create plots

of indices and/or perform in-depth investigation (both in time and frequency domains) for troublesome loops. Reports can be configured to easily compare performances over different time-periods or even over different operating modes or production campaigns. The reports enable the maintenance team to focus on the most important process control problems.

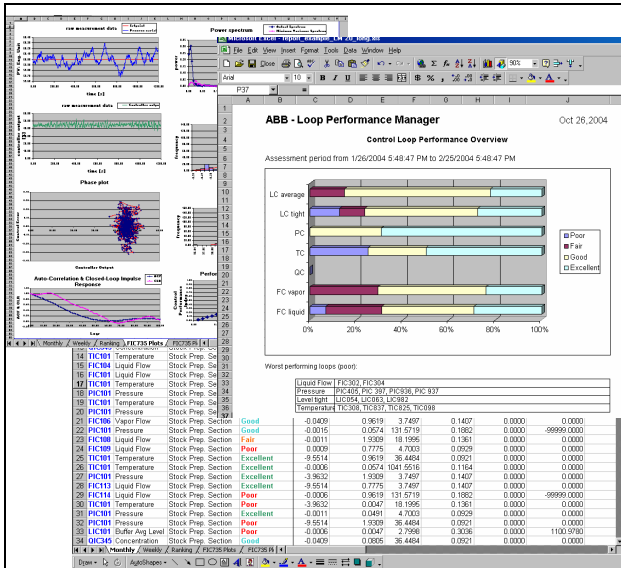


Figure 4 - Reports Example

### C. PDA description

To complete the portfolio of tools for the control engineer, LPM embeds the Plant-wide Disturbance Analysis (PDA) toolkit, an innovative software module for identification and classification of process upsets. The PDA component has its roots in the cutting-edge research [7, 9-11] developed mainly by the University of London team, led by Prof. Nina Thornhill and has been developed in a joint effort by researchers and software engineers in UK, Norway, Germany and Italy. Able to focus attention towards the actual root causes, it represents the state of the art for investigation of upsets and disturbances in chemical, refining, oil and gas and, more generally, continuous industrial processes.

PDA underlying philosophy is based on a Top-Down approach that perfectly complements the inherent Bottom-Up approach of the Loop Auditing component [12]. In taking a plant-wide approach the starting point is to visualize the behavior of the whole plant using process measurements from routine operation and then to drill down into promising areas to uncover and solve problems.

Moving through a guided, step-by-step wizard, the user can:

- Detect the presence of one or more periodic oscillations revealed by a regular pattern in the measurements;
- Detect non-periodic disturbances and plant upsets;
- Look for commonalities in the patterns of the disturbance signals and cluster loops with similar behavior

- Identify, for each cluster, the candidate to be the disturbance originator.

The last feature is of paramount importance because helping to focus on the actual root cause. The increasing heat integration and interconnectivity of streams in process plants makes extremely difficult to spot where the upset could have been originated. Being able to recognize that, say, a given oscillation affecting 20 loops can be solved just retuning a single pressure controller, will reduce of an order of magnitude the maintenance effort.

PDA features innovative solutions both in the algorithmic structure and in the result and dependencies visualization, which have been designed to help the user to immediately catch the essential information about process and instrumentation performances.

PDA utilizes autocovariance functions analysis for oscillation detection while spectral principal component analysis is used for the identification of non-periodic disturbances. Spectral PCA is insensitive to the time delays caused by plant dynamics and thus offers benefits over time-domain PCA. In spectral PCA, signals having the same frequency components appear as clusters regardless of their time delays. When large data bases are used in a plant audit to find groups of measurements having similar characteristics it becomes challenging to present the results of a multivariate analysis in a clear, effective way. While PCA is able to reduce several hundred measurements to, say, a dozen principal components, the issue of presenting twelve-dimensional models to the user still remains.

LPM utilizes a hierarchical classification tree for visualization of the clusters in a high-dimensional spectral PCA model. The key elements in the procedure are an agglomerative hierarchical clustering algorithm and a recursive algorithm to create the tree (see [13] for more details). Each item in the tree represents the power spectrum from one measurement point in the process and the vertical axis is an angle measure that indicates how similar the spectra are to one another. An example of hierarchical spectral classification tree in LPM is shown in Figure 5.

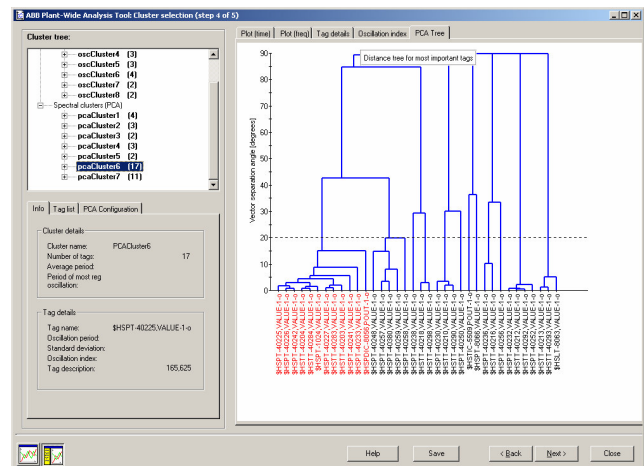


Figure 5 – Example of Hierarchical Classification Tree

The height of a horizontal bridge connecting two tags is the angular distance giving a measure of how similar their corresponding spectra are. The lower the bridge the more similar are the spectra. The variables highlighted in red on the left of the screen are clearly identified as belonging to a single cluster, because of the low vertical position of the connecting bridge.

The benefit of the PDA technology is the ease of maintenance of basic control functions and the reduction of the man hours required. In particular, the isolation of likely root causes directs attention precisely to the area that has the highest probability to be in failure and thus cuts down the time spent for control loop maintenance purposes.

#### D. Additional Utilities

The primary scope of LPM is to provide the right information to the right people at the right time. As such it includes some utilities designed to maximize the usability, comfort and accessibility. Among the others, some are worth to be mentioned:

- **Bulk Configuration:** it is a utility which allows importing configuration data for large number of loops directly from the DCS database. This reduces dramatically configuration and project start-up efforts, eliminating time-consuming, error-prone manual data input.
- **Server Status Monitor:** as seen Auditing is (as it must be) mainly a background running application. This is very non-invasive but could result tricky if something goes wrong in between two weekly report generations (either to the OPC connection or to the underlying software infrastructure). The Server Status Monitor can be seen as a watch-dog utility able to provide information and diagnostics on the operation of the LPM Auditing routines.
- **LPM Web Client:** this option allows accessing and even configuring LPM reports and tuning logs from remote locations. The obvious advantage is that the maintenance engineer can monitor system health directly from his desk.

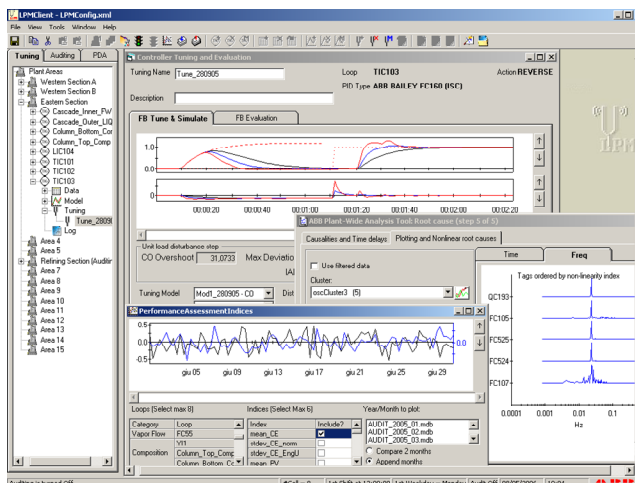


Figure 6 – LPM a Single Environment for Disturbance Analysis, Cause Detection and Remediation

All the modules and related utilities are managed by a single human interface, increasing synergies and reducing drastically the training and familiarization effort. Figure 6 provides a glimpse of how LPM HMI looks like to the user.

### III PRINCIPLE WORK FLOW

The three modules available into LPM have been designed and developed to work in synergy in order to provide the maximum assistance to the control engineer engaged in maintaining and improving plant automation performances.

This can be best seen through a virtual example. Jack, the control engineer in charge of process automation at BIGPROCESS Inc. comes back to the plant on Monday morning and from his desk uses the LPM Web-client to remotely open the freshly generated weekly report and check if everything is running smoothly on the 2000 loops installation he has to manage. Immediately the latest report tells him that 45 loops have decreased dramatically their performances moving from the status of GOOD to the status of POOR.

Instead of going into panic, Jack extracts the trends of the 45 bad-behaving loop PVs and feeds them into the LPM-PDA software he has installed in his workstation. Moving quickly through the wizard he realizes that the 45 potential problems can be clustered into three groups: this is quite reassuring because it tells that the 45 troubles are just effects of only 3 causes. At this point he proceeds with the software which identifies three possible culprits: 2 flowrate loops, FIC-123 and FIC-303 and, 1 temperature loop, TI-376, are the candidates of the mishaps. Jack goes back to the report and opens the Detailed Loop Report page for the loops under investigation: loop indices and diagnosis spot that there are indications that the troubles are due to stiction for loop FIC-123, sensor reading for TI-376 and too aggressive tuning for FIC-303.

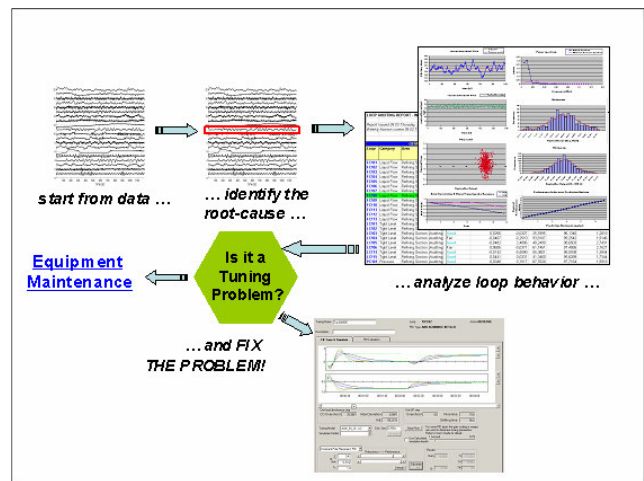


Figure 7 – LPM Work Flow

Jack issue a request to the Maintenance Department for checking the valve on FIC-123 and the thermocouple for TI-376 and collects himself some fresh data from loop

FIC-303. Minutes later he has determined the new optimal tuning set with LPM-Tuning, which inserted into the DCS will fix the problem.

In a couple of hours Jack has identified, addressed and fixed problems that otherwise would have been undetected for months mining the performances of the process and potentially having an impact on the bottom line of the production unit. Figure 7 shows a schematic representation of the LPM Principle Work Flow.

#### IV APPLICATION TO A TEST CASE

The technology described in this paper and its industrial implementation into LPM is successfully in operation at several customer sites in different continents. One of the most interesting application has been realized at the Termoli (Italy) GE – Bayer Specialties plant for advanced material production. The plant is characterized by a complex chemical process, controlled by more than 500 feedback control loops. In the last years, the Plant Control Manager has been personally engaged in improving and updating plant automation, on the road to process optimization and plant profitability. After some years in which GE-Bayer carried out significant improvement in the automation system with the addition of new DCS hardware and software components, it was recognized that the further step was the optimization of the existing system taking into account process, field devices (like actuators and sensors) and control systems altogether. In other words all the elements having a role in a control loop.

As an additional motivation, in 2006 the Company Headquarter required the plant engineers to achieve two ambitious objectives:

- GE-Bayer launched a 6-sigma program called "Stable Operations", aiming to stabilize all production phases, in order to improve product quality consistency, with higher plant reliability and availability and with drastically reduces inventories.
- GE-Bayer required to reduce the energy consumption of the plant of 10%

The answer to this challenge and tough requirements included as a cornerstone the extensive exploitation of LPM.

First activity was to retune many loops, whose performances were clearly sub-optimal or even not satisfactory at all. In a short time more than 250 loops (TIC, FIC, PIC, LIC, and pH) have been retuned and it has been possible to remove many oscillation problems caused by excessively aggressive setting of PID parameters.

After the general plant retuning, Customer activated the Auditing functionality to monitor the behavior of the control system. In the last six months the software has been on-line collecting data and generating reports every week. Custom reports have been configured to independently address each main process area, so to ease problem identification and related maintenance actions.

As an example let's take a look at one of the report generated on May 21<sup>st</sup> on the process area labeled CNT (Figure 8). The software has identified loops in each of the four possible Performance grades (Excellent, Good, Fair, Poor). The maintenance engineer could then start looking at the worst performing loops (the ones rated POOR), while been reassured about the loops rated as GOOD or EXCELLENT.

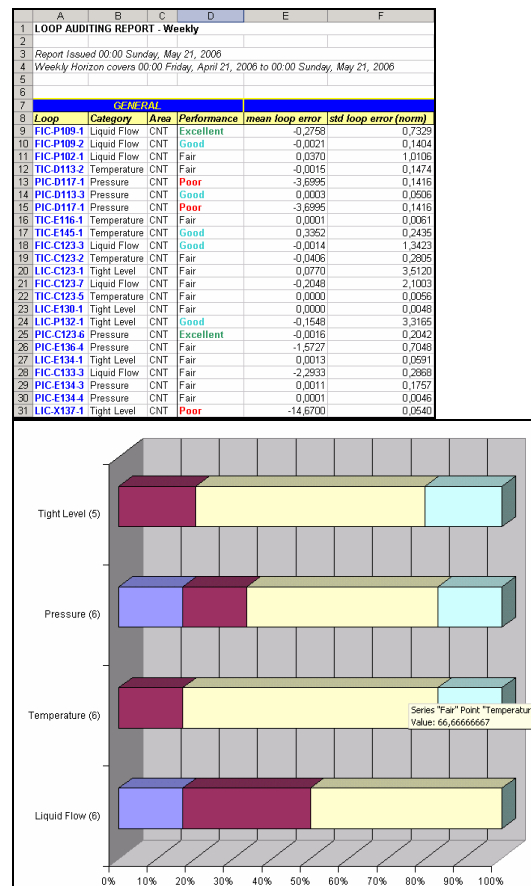


Figure 8 – CNT Area Report

To understand why PIC-C123-6 has been rated as Excellent and PIC-D117-1 Poor, let's dig a little bit in the detailed information layer, i.e. the diagnosis and indices. Table 1 compares the "diagnoses" for the two loops.

Loop Diagnoses	PIC-C123-6	PIC-D117-1
Overall Performance	<b>Excellent</b>	<b>Poor</b>
Tuning problem	0%	5.88%
Loop oscillatory	0%	100%
SetPoint oscillatory	0%	0%
Significant external disturbance	n.a.	n.a.
Significant nonlinearity	n.a.	0%
Valve stiction	n.a.	0%
Valve leakage or zero error	n.a.	n.a.
Valve size incorrect	0%	85%
Excessive valve action	20%	0%
Data unreliable	0%	0%

Table 1 – Diagnoses Comparison

From Table 1 it is easy to recognize that Loop PIC-117-1 suffers of oscillation problems and the most probable reason is the Incorrect Valve Size.

In order to reach a deeper insight about the actual loop operation, the Process Engineers can turn to the Performance Indices.

Table 2 reports the most important indices related to the 2 loops of Table 1. Looking at loop PIC-D-117-1 it is confirmed that Control Error is oscillating (index equal to 0.39) with a period of 402s and that the Control Output is working in saturation, with a Control Error mean equal to -3.69.

Taking into consideration Loop PIC-C123-6, Table 1 shows an “Excellent” behaviour with no real problem highlighted, and just a warning on a moderate chance of having excessive valve movement (20%). Again Table 2 gives more details through the key performance indices. LPM calculates very good values for loop PIC-C123-6: no oscillation (negative “oscillation index CE” means that the Control Error doesn’t oscillate) and no saturation in the Control Output (“CO saturation index” equal to zero), very good tuning performance (Harris index close to 1, and high number of setpoint crossing 39.32%), and Control Error very limited (standard deviation  $\sigma_{CE}=0.20\%$ ).

Loop Indices	PIC-C123-6	PIC-D117-1
mean loop error	-0.0016	-3.69
std loop error (norm)	0.20%	0.14%
CO saturation index	0.0000	99.6000
setpoint crossing index	39.3250	0.0000
Harris index	0.9475	0.0005
oscillation index CE	-0.86	0.39
oscillation period	n.a.	401.9 s
oscillation amplitude	n.a.	44.97%

Table 2 – Selected Indices Comparison

In order to fully investigate the loop behaviour, LPM allows for a selected number of loops (max. 10 per report) to show the actual data collected in the first data batch of the week. The example for PIC-C123-6 is presented in Figure 9, where the following 6 charts are shown:

- top left: Setpoint and Process Variable in the time domain,
- central left: Control Output in time domain,
- bottom left: Control Output vs. Control Error,
- top right: power spectrum of the actual Control Error and of the Control Error in case of the best possible controller (defined as Minimum Variance Controller)
- central right: Control Output statistical distribution
- bottom right: Control Error statistical distribution

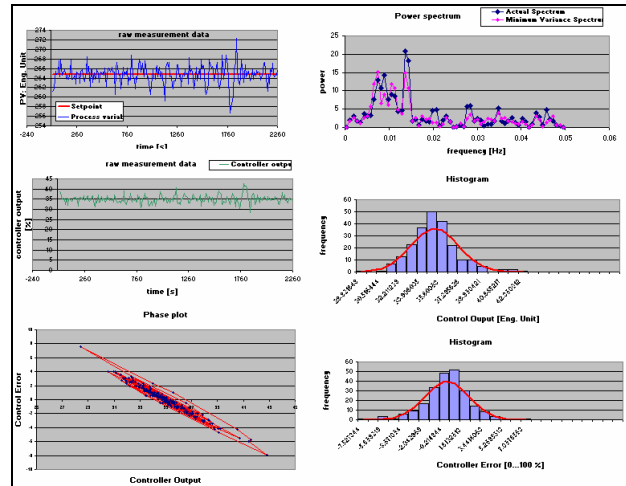


Figure 9 – PIC-C123-6 Detailed Analysis

Table 2 confirms the excellent behavior of Loop PIC-C123-6. The top left chart confirms that Process Variable remains close to the Setpoint. Top right chart shows that there are some oscillation in the Control Error, with the most important frequency component at 0.0137 Hz, corresponding to an oscillation period of 73 sec; however this oscillation is of the same level of the other spectrum components. Figure central right and bottom right show that the statistical distribution are close to be Gaussian, as should be for a well controlled system.

The results here presented show that LPM is able to discriminate the loops requiring more care and it is able to give to the maintenance engineers suggestion on how direct the intervention on loop with problems. Taking into account the two examined loops PIC-C126-6 and PIC-D117-1, LPM says to plant engineers that PIC-C123-6 is working without major problems, while it is necessary to investigate the status of PIC-D117-1 and LPM suggest verifying the design of the relevant valve, because it is working always in saturation.

The experience gained with LPM at the General Electric plant has been very impressive and is giving tangible results and a big help to plant engineers engaged in fulfilling the requirements from the Central Headquarter. Customer has estimated that the computer aided retuning and performance monitoring activity has resulted into energy consumption savings, which are exceeding expectations. For instance, after the first months, the improved control is allowing a reduction in utility consumption of up to 5% of the methane used as fuel for process steam generation.

#### ACKNOWLEDGMENT

Two of the authors (P.B. and N.B.) would like to thank Mr. Alexander Horch of the ABB Research Center of Ladenburg (Germany) for his valuable and friendly help towards the writing of this paper.

## **Acronyms**

AM	<i>Asset Management</i>
CE	<i>Control Error</i>
CLCM	<i>Control Loop Condition Monitoring</i>
CO	<i>Control Output</i>
DCS	<i>Distributed Control System</i>
HMI	<i>Human-Machine Interface</i>
HTML	<i>Hyper Text Mark-up Language</i>
LPM	<i>Loop Performance Manager</i>
MVC	<i>Minimum Variance Controller</i>
OP	<i>Output (to) Process (same as CO)</i>
OPC	<i>Ole for Process Control</i>
PCA	<i>Principal Component Analysis</i>
PDA	<i>Plant-wide Disturbance Analysis</i>
PID	<i>Proportional, Integral, Derivative (controller)</i>
PV	<i>Process Variable</i>
SP	<i>Set Point</i>

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