Review of State-of-the-Art PID Controller Tuning Software

1008040

Review of State-of-the-Art Controller Tuning Software

1008040

Technical Update, March 2004

EPRI Project Manager

R. Torok

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

EPRI Instrumentation and Control Center

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520. Toll-free number: 800.313.3774, press 2, or internally x5379; voice: 925.609.9169; fax: 925.609.1310.

CITATIONS

This report was prepared by

EPRI I&C Center
714 Swan Pond Road
Harriman, TN   37748

Principal Investigators
R. Hubby
C. Taft

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Review of State-of-the-Art PID Controller Tuning Software, EPRI, Palo Alto, CA: 2004. 1008040.

ABSTRACT

Power plant control systems must perform well if the whole plant is to perform well. Proper control system tuning is one of the key foundations on which control system performance is built. Proportional-integral-derivative (PID) controllers are the most common industrial controllers by far, so they are the primary candidates for overall control system tuning. PID tuning has generally been done empirically in the power industry, but today there are many computer programs to assist engineers and technicians in the tuning process. These programs are not widely used in the power industry, at least partly because power plant control systems are more complicated than the typical industrial control systems. Many of the programs have not supported the tuning of such complex control loops. In this report, PID tuning computer programs are reviewed. The general capabilities of such programs are described and power plant specific requirements are discussed. A table listing the features provided by each of seven programs is also included. Special attention is paid to features needed for the more complex power plant control loops using feedforward and cascade strategies. This report is the latest in a series of reports on power plant control system tuning. The ultimate goal of the control system tuning project is to produce and demonstrate an automated computer program suitable for power plant control system tuning.

CONTENTS

LIST OF TABLES

1 INTRODUCTION

Power plant control systems must perform well if the whole plant is to perform well. Proper control system tuning is one of the key foundations on which control system performance is built, and proportional-integral-derivative (PID) controllers are the dominant control technique used today. PID tuning has generally been done empirically in the power industry, but there are many computer programs to assist engineers and technicians in the tuning process. These programs are not widely used in the power industry, at least partly because power plant control systems are more complicated than the typical industrial control systems. In the early days of these programs, they did not support tuning of the more advanced type loops. In this report, PID tuning computer programs are reviewed. The general capabilities of such programs are described, and power plant specific requirements are discussed. A table listing the features provided by each of seven programs is also included. Special attention is paid to features needed for the more complex power plant control loops that use feedforward and cascade strategies.

BACKGROUND

Control system tuning has been an important topic for EPRI members for the past several years. As a result, EPRI initiated a project in 2001 to investigate developing automated tools for control system tuning. Over the past five years, EPRI produced three short reports dealing with power plant control system tuning and tuning assessment [1] [2] [3].

Almost all power plant control systems are tuned empirically today. Often the control system vendor startup engineer performs the tuning during initial unit operation. Occasionally, the plant staff will perform the initial tuning. Even if the initial tuning is done properly, there are many reasons why the control system might need to be retuned in the future. A common situation today is for the plant to be modified in some way, often for better emission control, and this alters the response of the boiler, necessitating new tuning. Another possibility is that the unit was originally planned for base load operation but is now being operated in a load following mode. Usually the tuning for these different operating scenarios would be different. For these and other reasons, there is an ongoing need for power plant control systems to be tuned.

In recent years there has been tremendous pressure on power producers to reduce staffing levels at plants in an effort to control operating costs. These staff reductions have often led to the retirement of the more senior specialists including those that may have known the most about tuning. Although the less senior staff members may be well qualified, they might not have enough experience with tuning to be proficient at it. This is where the computer based tuning tools can lend a helping hand. They provide some of the technical expertise that the technician may not have.

There are many commercially available software programs for PID controller tuning. These programs usually operate on a PC that is interfaced to the plant control system. Process data from the operating plant is sent to the PC, where it is used to estimate the characteristics of the loop being controlled. These loop characteristics are then used to calculate the "best" tuning settings for the loop. The concept of "best" tuning is not as simple as it sounds. What one expert tuner considers best, another tuner may not care for. Different loops also require different types of responses. So part of the tuning problem is to determine what the tuning objectives are for each loop, as discussed in [3].

Tuning simple PID control loops is relatively easy to do, and any of the packages examined in this report should be able to do an adequate job for that application. Unfortunately, many, if not most, power plant control loops are not simple. It is very common for cascade control schemes to be used in boiler control systems, and many loops have feedforward controls and multiple drive units as well. For this reason, this report notes those program features that are particularly useful for power plant application.

Many of the vendors who provide PID tuning software also provide software for monitoring control loop performance. In this report only the PID tuning software is considered.

Chapter 2 of this report discusses the desired basic and power plant specific features of PID tuning software in nine major categories, including: (1) PID Tuning, (2) Control Loop Diagnostics, (3) Process Modeling, (4) Simulation, (5) Data Analysis, (6) Software Configuration, (7) Online and Offline Capabilities, (8) Connectivity, and (9) Vendor Control Systems Supported. Among the identified features in Chapter 2 for power plant applications are support for: (1) cascade and feedforward control strategies; (2) more sophisticated process modeling, such as inverse response processes e.g., drum level; (3) advanced data analysis; and (4) end element positioning performance (damper drives and control valves).

Chapter 3 provides a table that identifies which vendor packages provide which features along with vendor contact information. Chapter 5 offers conclusions and recommendations on ways to proceed with the ultimate project goal of developing better automated tools for power plant control system tuning.

2
TYPICAL PID TUNING PROGRAM CAPABILITIES

As a way of comparing the capabilities of the software packages under review, ten major categories of features have been identified. In this chapter, each of these categories is described, including individual features within each category. No single supplier provides all of the capabilities described in the sections below. Table 3-1 provides a tabulation of the capabilities of each of the software systems evaluated.

PID Tuning

Obviously the ability to perform PID tuning is a requirement of these packages. Within the PID tuning function the following basic capabilities/features are desirable:

- Optimize tuning for setpoint tracking or disturbance rejection (load change). Some loops are designed for the setpoint to track a changing demand signal while others have a constant setpoint and are designed to reject disturbances, such as load changes, which tend to force the process variable away from the setpoint. The optimum tuning for these two situations is usually different, so the software should accommodate both.
- User specified performance criteria, such as maximum overshoot, rise time, settling time, time constant. In order to optimize the tuning settings, the software has to know which criteria are the most important to the user. There are many ways of specifying desired control system response, ranging from a qualitative fast or slow to a quantitative measure, such as, overshoot or rise time.
- User selectable tuning method, such as lambda, internal model control, Zeigler-Nichols, minimum integrated error. There are several algorithms available to compute tuning parameters and each produces different results. The software should allow the user to examine results from several algorithms to determine which is best for the selected application.
- User selectable trade-off between speed of response and robustness (stability margin). On any control loop there are ranges of tuning parameters which provide stable response. In general a faster response will be closer to instability than a slower response. The user should be able to choose whether the faster response is more important than the improved stability margin.
- The system should provide quantified measures of process variable response, actuator movement and robustness. Quantified measures allow direct comparison between various responses.

For power plant applications, the following additional capabilities/features are desirable:

- Tuning for inner and outer loops in a cascade control scheme. Cascade control schemes are very common in power plant control systems, so it would be very useful if this capability was provided.
- Tuning of feedforward gain and lead/lag parameters. Dealing with feedforward tuning is another common power plant need.
- Advice on use of derivative action on process variable or loop error. Derivative action is usually only applied to the process variable, but if setpoint filtering is used, it may be useful to apply it to the loop error signal instead.
- Advice on use of setpoint filtering. For control loop designed for setpoint tracking, it can improve loop performance by providing a filter on the setpoint input. This is sometimes referred to as a two degree of freedom controller.
- Tuning for deadtime compensation schemes such as Smith predictor. There are a couple of processes in power plants where deadtime plays an important role. For these applications, the ability to investigate deadtime compensation control schemes is a nice feature.

Process Modeling

The heart of any PID tuning software package is the system's ability to accurately model the process being controlled. The commonly used technique for determining the process model is to use input and output data from the process. This technique is referred to as model identification or system identification in the technical literature. Many common processes exhibit a response characteristic that approximates a first order lag plus a deadtime. As a result, most packages offer models with this structure as a minimum. However, not all processes can be modeled with a first order lag plus deadtime structure, so it is important to offer a variety of other process model structures. The more capable the process modeling function is, the more accurate models it can produce, and greater model accuracy leads to better tuning parameters.

To address power plant tuning needs, the process modeling function within the tuning package should provide the following basic features:

- A variety of process model structures including self-regulating, integrating, and differentiating models should be provided. Self-regulating systems are the most common in process control and have the characteristic that a step change on the input causes a bounded response on the output. An integrating process is one in which a step change on the input causes an unbounded response on the output. Level control in a drum or tank is an example of an integrating process. A differentiating process is one where a step change in the input causes a transient spike in the output before it returns to its initial value. Megawatt output in response to a change in turbine valve position is an example of a differentiating process.
- Models should be capable of representing process deadtime response also. Steam temperature response to spray valve position change is a process that exhibits deadtime in its response.
- A variety of process excitation signals should be available for model identification. Step inputs and impulse type inputs are needed at a minimum.

- The system should be able to identify a model using closed loop or open loop data. There are some loops which plant operators are not willing to put in manual mode (open loop) in order to do a step response test. For these loops the control can be left in automatic and a step change made to the setpoint.
- The system should provide a quantitative measure of the accuracy of the identified model. This is important for the user to know, since an inaccurate model will lead to incorrect tuning parameters.
- The system should provide plots that overlay the actual test data with the predicted response of the model for a visual indication of model accuracy.
- The system should display the mathematical equation for the identified model as a transfer function.

In addition to the basic functional desires described above, the following advanced functions are desired for power plant applications:

- The system should provide the ability to model cascade control processes. While cascade control loops can be analyzed in two steps, first the inner loop and then the outer loop, it is much easier if the system deals with the cascade model structure directly.
- Additional test excitation signals should be provided, including pulse doublet (up and down pulses), pseudo-random binary sequence (PRBS), and sine wave.
- The ability to develop more general, multivariable models may be useful in some situations where feedforward signals are used or where there is considerable interaction between loops.

Simulation

A necessary function for all tuning packages is the ability to simulate the process being tuned in both open-loop (manual) and closed-loop (automatic) operation. This enables the user to see the predicted performance of the control loop after the tuning change and compare it to the current performance.

The simulation function within the tuning software package should provide the following basic features:

- The simulation function should be able to simulate open and closed-loop operation of the control loop.
- Display the simulation results in a trend plot.
- Overlay the simulation results with the current control loop operation.
- The data from the simulation should be exportable in a variety of common file formats such as CSV (ASCII) and Excel.

In addition to the basic functions listed above, the simulation function should also provide these features for power plant applications:

- The ability to incorporate process noise into the simulation.

- The capability to simulate cascade control loop responses.
- The ability to simulate feedforward and disturbance variable impacts on the control loop.

Control Loop Diagnostics

Although control loop diagnostics are not strictly part of PID controller tuning, they are included in this report because several packages include capabilities in this area. Most of the diagnostic capability is related to the final actuator in the control loop. This is appropriate because many control loop problems that appear to be tuning problems are actually problems with field devices such as actuators.

Some of the common types of loop problems that can be diagnosed by tuning packages include:

- Actuator saturation at the open or closed position. In some loops actuator saturation is quite common such as steam temperature control spray valves. If saturation occurs during a model identification test, the test results will probably not be usable.
- Actuator hysteresis, which is also referred to as deadband, backlash, and stiction. This can be caused by mechanical play in linkages, valve stem packing too tight, or too much deadband in an electric drive’s position controller. Too much hysteresis will cause sustained cycling in the loop output.
- Excessive noise in the loop. The noise can be real process noise or induced noise from electromagnetic interference. In either case, filtering may be able to remove most of the noise without degrading control loop performance. Excessive noise can cause accelerated actuator wear and tear.
- Actuator non-linearity.

Data Analysis

All tuning packages can utilize operating data from the control system in order to calculate desired tuning parameters. However, it is also desirable to provide additional data analysis capabilities, because more can be learned about the process being controlled through different types of analysis.

The data analysis function within the tuning software package should provide the following features:

- Basic statistical analysis of all signals including mean, minimum, maximum, standard deviation.
- Quantification of process noise level. This can indicate the need for more filtering on the process variable.
- Histogram analysis of data provides a different view of loop error signals and provides a convenient way to compare performance before and after tuning changes.
- The user should be able to view the data in trend or tabular form.

- Trend displays should allow the data to be displayed on overlayed or separate axes. Windowing, panning and zooming functions should also be provided for the trend displays.
- Storage of data for later retrieval and analysis.
- Output of data in a variety of common file formats including CSV ASCII and Excel for analysis by other programs such as Excel or MATLAB.
- The user should have the capability to manually edit the data during the analysis process to remove outliers or fill in obviously missing pieces.

In addition to the basic functions listed above, the data analysis function may provide the following features for power plant applications:

- Power spectral density (PSD) analysis to understand frequency content of signals.
- Autocorrelation of signals to quantify their randomness. This is mainly used in analyzing the error between the process data and the identified model of the process data. If the error is not a random signal, the model may need to be modified to improve its accuracy.
- Cross-correlation of signals to understand coupling between loops. If two signals are correlated, there is coupling between the signals and a feedforward signals may be useful to improve the control loop performance.

Software Configuration

When the tuning software is first connected to a control system, it must be configured to match to control loop of interest. In other words, the user must tell the software which variable in the control system is the loop's process variable, which is the setpoint, which is the controller output, etc. If the software supports the control platform well, this configuration can be a fairly easy process, typically done through a graphic template. If the system does not support the control platform, the user should still be able to import data into the program and manually configure the software to analyze the loop of interest. There are no power plant specific additional features desired.

Online and Offline Capabilities

Online capabilities refer to the ability of the software to communicate directly with the control system in real-time to retrieve process and other data needed for tuning analysis. Offline capabilities are those functions that can be performed when the software is not connected to the control system. . The on-line and offline desired capabilities are listed below:

Online

- The system should be able to receive loop operational data from the control system in real-time.
- The system should be able to retrieve tuning parameters from the PID controller being tuned.

- The system may be able to retrieve other configuration data from the control loop such as signal scaling, input filtering, and function generator curves.

Offline

- The tuning software should allow data to be imported into the program from data file in a variety of common formats including CSV ASCII and Excel.
- The tuning software system should provide all the same tuning and analysis features listed above when operating in an offline mode and using imported data.

Connectivity

In order for the system to provide on-line tuning capability, it must have a communication interface with the control system. The communication interface can be a proprietary system or can use one of several industry standards such as network dynamic data exchange (NetDDE) or OLE for process control (OPC) to maintain real-time connections with PID loops, updating all process parameters at every sampling interval.

Vendors Control Systems Supported

The vendors to be supported include the major vendors who serve the power industry. Not all self-tune software suppliers interface to all of the major vendors. By providing support for a particular vendor's system, the tuning software should have the following features:

- A real-time data interface to the control system as described in the Connectivity section above
- Knowledge of the engineering details of the PID algorithm used by the vendor. There are many different forms of PID control algorithms, and if a control system is supported by the tuning software, the software should know details such as whether the controller expresses proportional gain as gain or proportional band.
- The software should know the parameter names of the PID tuning related parameters in the control system and should offer a default loop configuration using the standard nomenclature.

3
SUMMARY OF PROGRAM CAPABILITIES

Table 3-1 summarizes the capabilities of the PID tuning packages reviewed. Every effort has been made to ensure the accuracy of this information, but errors may exist. In some cases, a product's features may not align exactly with the categories identified in the table and so the determination of whether a feature is provided is open to some interpretation.

Vendor Information

Below are the software package names that are included in this review along with contact information for the companies that developed them.

ExperTune
ExperTune Inc.
4743 Sonseeahray Drive
Hubertus, WI 53033-9728 USA
Phone: (262) 628-0088
Fax: (262) 628-0087
E-mail: sales@expertune.com
Web: www.expertune.com

Intune
ControlSoft, Inc.
5387 Avion Park Drive
Highland Heights, OH 44143 USA
Phone: 440-443-3900
Fax: 440-443-0249
e-mail: info@controlsoftinc.com
Web: www.controlsoftinc.com

Protuner 32
Techmation
2121 South Mill Avenue
Suite 111
Tempe, AZ 85282 USA
Phone: (480) 968-9946
Email: techmation@protuner.com
Web: www.protuner.com

Control System Tuning Package (CSTP)
The Israel Electric Corporation
Generation and Transmission Division
P.O. Box 10
Haifa 31000, Israel

ARDAN-PIC Ltd.
P.O. Box 1704
32 Habanay St.
Holon 58817, Israel.
Web: www.ardan-pic.co.il/CSTPsite

EngineSoft
P.O. Box 877
Tempe, Arizona 85280-0877
Phone: (480) 965-9476
Email: sales@pidtune.com
Web: www.pidtune.com

TuneWizard
PAS, Inc.
16055 Space Center Blvd.
Suite 600
Houston, Texas 77062 USA
Phone: (281) 286-6565
Email: sales@pas.com
Web: www.tunewizard.com

Model Identification and PID Tuning
Control Arts, Inc.
616 Bobbie Drive
Danville, CA 94526 USA
Phone: (925) 838-2062
Fax: (925) 838-1866
Email: sales@controlartsinc.com
Web: www.controlartsinc.com

Loop Performance Manager (LPM)
ABB, Inc.
29801 Euclid Ave.
Wickliffe, OH 44092 USA
Phone: (440) 585-5529
Fax: (440) 585-7796
Email: don.frerichs@abb.us.com

Miscellaneous Comments on the Tuning Packages

Below are some comments on various aspects of the tuning programs that do not fit into any category in Table 3-1

CSTP

- CSTP was developed using the MATLAB software platform and requires MATLAB to run. In addition to basic MATLAB, it also requires Simulink and two toolboxes, the Control System Toolbox and the System Identification Toolbox. A new version is under development that does not require the MATLAB software.
- CSTP is specifically designed for power plant applications. The developers work for a power company.
- This package provides more process modeling capability than most and also provides many specific model structures for power plant processes.
- No online capabilities.

Intune

- Intune has licensed several popular control system vendors to sell a special version of their software that is customized for the vendor's specific control system.

ExperTune

-
- The package has the most extensive feature set.

pIDTune

- Only accepts data from the MATLAB environment.
- As indicated by the capitalization of the product's name, this package emphasizes its model identification capabilities.
- No online capabilities

Table 3-1
Summary of PID Tuning Software Features

Features	Power	CSTP	Intune	Protuner 32	ExperTune	pIDTune	ABB LPM	TuneWizard	Model ID and PID Tuning
PID Tuning									
Tuning for Setpoint Tracking or Disturbance Rejection		yes	yes	yes	yes	yes	yes	yes	yes
Optimization criteria									
Overshoot		yes		yes	yes		yes		
Rise time		yes		yes		yes	yes		yes
Settling time		yes		yes			yes		
Minimum integrated error					yes		yes		
Tuning Methods									
Lambda					yes		yes		
Internal Model Control			yes			yes	yes		yes
Zeigler-Nichols					yes				
Tradeoff between Speed and Stability		yes	yes		yes	yes			yes
Quantified Performance Measures									
Process Variable Response		yes					yes		yes
Robustness					yes		yes		
Actuator Movement		yes			yes		yes		yes
Cascade Loop Tuning	P				yes		yes		
Feedforward Tuning	P				yes		yes		
Derivative action advice	P	yes							
Setpoint Filtering	P	yes			yes	yes	yes		yes
Deadtime Compensation Tuning	P						yes		

Table 3-1, continued

Features	Power	CSTP	Intune	Protuner 32	ExperTune	pIDTune	ABB LPM	TuneWizard	Model ID and PID Tuning
		Packages							
Process Modeling									
Model Structures									
Self-regulation - maximum # zeros of transfer function		2	0	0	1	>3	1	0	1
Self-regulation - maximum # poles of transfer function		3	1	2	2	>3	3	1	2
Integrating - maximum # zeros of transfer function		2	0	0	0	>3	1	0	1
Integrating - maximum # poles of transfer function		3	2	2	1	>3	4	2	2
Differentiating - maximum # zeros of transfer function		2	-	-	-	>3		-	1
Differentiating - maximum # poles of transfer function		3	-	-	-	>3		-	2
Other						yes			
Deadtime or Time delay		yes	yes	yes	yes	yes	yes	yes	yes
Excitation Signals									
Step		yes	yes	yes	yes	yes	yes	yes	yes
Impulse		yes			yes	yes	yes		
Pulse doublet	P	yes			yes		yes		
PRBS	P	yes			yes	yes			
Sine wave	P	yes							
Closed loop identification		yes	yes		yes		yes		yes
Quantified model accuracy		yes			yes		yes		
Overlayed plots		yes			yes		yes		yes
Mathematical equation display		yes			yes		yes		yes
Cascade control loops	P				yes		yes		
Multivariable models	P	yes			yes		yes		yes

Table 3-1, continued

Features	Power	CSTP	Intune	Protuner 32	ExperTune	pIDTune	ABB LPM	TuneWizard	Model ID and PID Tuning
Simulation									
Open and Closed-loop Response					yes		yes		
Display results in trend plot			yes		yes		yes		
Overlay plots		yes	yes		yes		yes	yes	
Export results data to file									
Incorporate Noise	P				yes				
Cascade loops	P		yes		yes		yes		
Feedforward loops	P		yes		yes	yes	yes		
Control Loop Diagnostics									
Actuator saturation		yes	yes		yes		yes		
Actuator hysteresis				yes	yes		yes	yes	
Noise filter analysis		yes		yes	yes	yes	yes	yes	
End element nonlinearities		yes					yes	yes	
Data Analysis									
Statistical analysis					yes		yes	yes	yes
Quantify process noise					yes		yes		no
Histograms			yes		yes		yes		
Tabular view of data									
Trend display options									
Overlayed			yes		yes		yes	yes	yes
Pan and Zoom					yes				
Data storage and retrieval					yes		yes	yes	
Output data to file				yes					
Edit data				yes	yes		yes		yes
Power spectral density	P	yes			yes			yes	yes
Autocorrelation	P	yes		yes	yes	yes	yes	yes	yes
Cross-correlation	P	yes		yes	yes	yes		yes	yes

Table 3-1, continued

Features	Power	CSTP	Intune	Protuner 32	ExperTune	pIDTune	ABB LPM	TuneWizard	Model ID and PID Tuning
		Packages							
Online and Offline Capabilities									
Online									
Read Operational data			yes		yes	no	yes	yes	
Read Tuning parameters			yes		yes	no	yes		
Read other parameters			yes		yes	no	yes		
Offline									
Data import from file		yes			yes	MATLAB Only	yes	yes	
Tuning and analysis		yes			yes	yes	yes	yes	
Connectivity									
DDE			yes	yes	yes			yes	
OPC			yes		yes		yes	yes	
Vendors control systems supported									
ABB(Bailey) Network 90, Infi 90, Symphony		yes	yes	yes	yes		yes		partial
Fisher Controls			yes		yes				
Honeywell			yes		yes	yes	yes	yes	
Moore Products			yes		yes				
Siemens			yes				yes		
Westinghouse WDPF and Ovation		yes	yes	yes	yes		yes		
Foxboro					yes				partial
Yokogawa					yes				
Rockwell Automation					yes				
Allen-Bradley					yes				
Modicon					yes				
Max Controls (Metso Automation)		yes							

4
CONCLUSIONS AND RECOMMENDATIONS

In this report, the capabilities of several commercial PID controller tuning software packages are reviewed. The information in this report is based on publicly available sources such as websites, product sales brochures and phone conversations with the vendors. It is not based on actual usage of the systems.

This information is intended to help plant personnel understand the capabilities of tuning software and to provide an initial screening of the commercial products. It is likely that all these packages will adequately tune simple PID control loops. A few have more extensive features and warrant further study and demonstration on an actual power plant application.

The next step in the EPRI control system tuning project is to develop a set of specifications for tuning functions specifically designed for power plant applications. EPRI envisions working with one or more of the vendors discussed in this report to develop these feature as an add-on to an existing package.

5
REFERENCES

1. *Power Plant Control System Tuning*, EPRI, Palo Alto, CA: 1999, TE-113653

2. *Automated Control System Tuning: Issues, Available Solutions and Potential for Improvement*, EPRI, Palo Alto, CA: 2001, 1004067

3. *Control System Tuning assessment Guidelines, EPRI, Palo Alto, CA: 2002, 1004425*

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

1008040

Printed on recycled paper in the United States of America

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com