Optimization using model predictive control in mining
Rockwell Automation is a member of the Association for Packaging and Processing Technologies (PMMI) – a trade association made up of more than 700 member companies that manufacture packaging, processing and packaging-related converting machinery, commercially-available packaging machinery components, containers and materials in the United States, Canada and Mexico.

PMMI members are the industry-leading solutions providers on your processing and packaging supply chain, and PMMI resources help you connect with them.

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Rockwell Automation at a glance

- **22,000 employees**
- **80+ countries**
- **$6.62B Fiscal 2014 sales**

Leading global provider of industrial power, control and information solutions

- **20+ industries**

Serving customers for 111 years
- Technology innovation
- Domain expertise
- Culture of integrity and corporate responsibility

2014 World's Most Ethical Companies®

WORLD’S MOST
ETHICAL COMPANIES®
WWW.ETHISPHERE.COM

Optimization using model predictive control in mining
Bringing you a world of experience

PAVILION SOLUTIONS
Helping you exceed your business goals

Innovation
- The most powerful predictive modeling software in the industry
- Enhancing the profitability of global manufacturers
- Delivering the highest ROI in the industry

Domain expertise
- Combining technology and application knowledge
- Targeted industries
- Best practices from multiple industries

Products
- Pavilion8®, Pavilion® RTO and Software CEM®
- Certified project managers
- Repeatable, measurable, auditable
- Risk management

Biofuels | Energy Optimization | Environmental | Food & Beverage | Minerals, Mining, Cement | Natural Gas Liquids | Polymers | Water/Wastewater
80 Countries | 20 Languages | 2500 + employees | Average 13+ Years' Experience | Single point of contact
Optimize your mining operation

Model predictive control solutions

Our mining capabilities help improve your operations
- Reduce grade variability
- Increase product recovery
- Reduce reagent consumption
- Reduce energy costs
- Increase throughput

Drive your operations to its maximum potential everyday with MPC

APPLICATIONS
- Crushing
- Grinding
- Flotation
- Thickening
- Material flow management
The facility: **Consists of MVs, DVs, CVs**

**Controlled Variables (CVs)**
Process variables that need to be maintained at a target or within a set range

**Controlled Constraint Variables (CCVs)**
Process variables that should not be allowed to violate limits (upper, lower or within a range)

**Manipulated Variables (MVs)**
Process variables you can adjust that affect the CVs (typically PID set-points)

**Disturbance Variables (DVs)**
Measured process variables that affect the CVs that are not MVs

Example:

- **CV = Speed (Maximize)**
- **MV = Accelerator**
- **CCV = Oil Pressure**
- **DV = Wind, Road Slick, Other Cars**
A simple MPC problem

GOALS
Maximizing ore flow (Operate to maximum constraints)

CV
CONTROLLED VARIABLES
Production rate

CCV
CONSTRAINTS
Belt maximum current
Belt maximum eight

MV
MANIPULATED VARIABLES
Feed gate
Belt speed

DV
DISTURBANCE VARIABLES
DV material density
So what makes **MPC** different?

<table>
<thead>
<tr>
<th>PID</th>
<th>MPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single input – single output controller</td>
<td>Multiple input – multiple output controller</td>
</tr>
<tr>
<td>Control based on current error</td>
<td>Control strategy based on a centralized approach</td>
</tr>
<tr>
<td>Poor ability to handle process delays, disturbances, interactions and non-linearities</td>
<td>All variables are simultaneously considered</td>
</tr>
<tr>
<td>Poor ability to handle different types of disturbances and set-point signal forms</td>
<td>Predictive control</td>
</tr>
<tr>
<td>Poor ability to handle constraints</td>
<td>Controller action based on current and anticipated future PV deviations from target</td>
</tr>
<tr>
<td>Poor ability to optimize (maximize or minimize)</td>
<td>Compensates for process delays, disturbances, interactions and non-linearities</td>
</tr>
<tr>
<td></td>
<td>Optimal control for all types of disturbances and set-point signal forms</td>
</tr>
<tr>
<td></td>
<td>Predictive handling of constraints</td>
</tr>
<tr>
<td></td>
<td>Capability to optimize process (maximize or minimize)</td>
</tr>
</tbody>
</table>
So what makes MPC different?

- PREDICTIVE CONTROL
- DIRECT PROPERTY VARIABLE CONTROL
- EXPLICIT DYNAMIC MODELS

EQUAL DISTRIBUTION

NO OVERLOAD
### MPC v Expert Systems

<table>
<thead>
<tr>
<th>EXPERT SYSTEMS</th>
<th>MPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilizes a model of operator reactions</td>
<td>Utilizes a model of process behavior</td>
</tr>
<tr>
<td>Rule-based/fuzzy logic control solver</td>
<td>Predictive control solver</td>
</tr>
<tr>
<td>Inefficient (operator comprehension)</td>
<td>Optimal (mathematical sense)</td>
</tr>
<tr>
<td>High maintenance required</td>
<td>Low maintenance</td>
</tr>
</tbody>
</table>
Pavilion8 MPC applications drive your existing infrastructure to **Maximum Performance**

- **CRUSHING**
- **GRINDING**
- **FLOTATION**
- **THICKENING**
- **MATERIAL FLOW**

- Reduced Product Variability
- Increased Product Recovery
- Mining Applications
- Reduce Reagent Consumption
- Reduce Energy Costs
Fine crushing
MPC | Fine crushing: Increasing throughput

CUSTOMER CHALLENGES
• Poor level control in the secondary and tertiary crushers
• Inability to keep secondary and tertiary crushers choked in order to maximize efficiency and minimize wear
• Loss of throughput
• Frequent line shutdowns
• Poor balancing of secondary and tertiary crushers

MPC BENEFITS
• Increase throughput by 2%
• Increase efficiency by 5%
• Decrease equipment wear by 5%
• Typical payback less than 1 year
OBJECTIVES

- Maximize crushing throughputs
- Keep feed bin levels within a range
- Control crusher levels
- Maintain crusher constraints
- Maintain belt constraints

**Fine crushing**

MPC
## Objective

- Maximize crushing throughputs
- Keep feed bin levels within a range
- Control crusher levels
- Maintain crusher constraints
- Maintain belt constraints

### Fine crushing matrix

<table>
<thead>
<tr>
<th>MV</th>
<th>2ary crushing throughput</th>
<th>2ary feed bin level</th>
<th>2ary crusher level</th>
<th>2ary belt 1 constraints</th>
<th>2ary belt 2 constraints</th>
<th>3ary crushing throughput</th>
<th>3ary feed bin level</th>
<th>3ary crusher level</th>
<th>3ary belt 1 constraints</th>
<th>3ary belt 2 constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>2ary feed belt 1 speeds</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2ary feed belt 2 speeds</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2ary crusher speeds</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3ary feed belt 1 speeds</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3ary feed belt 2 speeds</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3ary crusher speeds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 2% increase in throughput
- 5% increase in efficiency
- 5% decrease in equipment wear
Grinding circuit

MPC | Grinding: Increasing throughput

CUSTOMER CHALLENGES

• Oscillatory behavior and deviation from set-point
• Poor control of product quality (size)
• Reduced throughput due to constraints
• Unnecessary mill wear (steel-on-steel)
• Mill not running at maximum energy efficiency

MPC BENEFITS

• Maintain product quality (size)
• Increase throughput by 2%
• Decrease energy usage by 2%
• Decrease maintenance cost by 2%
• Typical payback less than 1 year
OBJECTIVES

- Maximize SAG mill fill
- Control SAG mill feed density
- Control hydrocyclone feed density
- Control P80 (product size)
- Maintain sump level within range
- Maintain hydrocyclone inlet pressure below limits
- Maintain circulating pump current below limits
- Maintain SAG mill bearing pressure below limits
- Maintain ball mill power draw below limits
- Maintain pebble recycle flow below limits
- Maintain SAG mill power draw below limits
Grinding circuit matrix

<table>
<thead>
<tr>
<th>Objective</th>
<th>SAG mill fill</th>
<th>SAG mill feed density</th>
<th>Hydrocyclone feed density</th>
<th>P80</th>
<th>Sump level</th>
<th>Hydrocyclone inlet pressure</th>
<th>Circulating pump current</th>
<th>SAG mill bearing pressure</th>
<th>Ball mill power draw</th>
<th>Pebble recycle flow</th>
<th>SAG mill power draw</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV SAG mill ore feed rate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV SAG mill water feed rate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV Sump water feed rate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MV SAG mill speed</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV Circulation pump speed</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DV F80</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DV Number of Hydrocyclone</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

**OBJECTIVES**

- Maximize SAG mill fill
- Control SAG mill feed density
- Control hydrocyclone feed density
- Control P80 (product size)
- Maintain sump level within range
- Maintain hydrocyclone inlet pressure below limits
- Maintain circulating pump current below limits
- Maintain SAG mill bearing pressure below limits
- Maintain ball mill power draw below limits
- Maintain pebble recycle flow below limits
- Maintain SAG mill power draw below limits

- 2% increased throughput
- 2% decreased energy usage
- 2% decreased maintenance cost
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CUSTOMER CHALLENGES

• Poor control of concentrate grade
• Lack of metal recovery control
• Excessive use of reagents

MPC BENEFITS

• Maintain concentrate grade to reduce product give-away or off-spec by 3%
• Increase metal recovery by 2%
• Reduce reagents by 3%
• Typical payback less than 1 year

Flotation

MPC | Flotation cell: Improving yield and reducing reagent cost
Flotation cell

**MPC**

**OBJECTIVES**

- Control concentrate grade (purity)
- Maximize metal recovery
- Control pH
- Control froth depth
- Control bubble speed or air hold-up
- Control bubble size distribution (BSD) or bubble surface area
- Maintain liberation within a range
## OBJECTIVES

- Control concentrate grade (purity)
- Maximize metal recovery
- Control pH and froth depth
- Control bubble speed or air hold-up
- Control bubble size distribution (BSD) or bubble surface area
- Maintain liberation within a range

---

### Flotation cell matrix

<table>
<thead>
<tr>
<th>MV</th>
<th>Concentrate Grade</th>
<th>Metal Recovery</th>
<th>pH</th>
<th>Froth Depth</th>
<th>Bubble size distribution</th>
<th>Bubble size or surface area</th>
<th>Liberation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector reagent flow ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Depressor reagent flow ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Modifier reagent flow ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Tail flow</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Air flow</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Frother reagent flow ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>P80 grinding</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Feed flow-grinding</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Feed density-grinding</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

- Keep concentrate grade at 3% reduced product give-away
- Maintain 3% reduced off-spec material
- Increase metal recovery by 2%
- Reduce reagents by 3%

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*Optimization using model predictive control in mining*
Flotation column
MPC | Flotation column: Improving yield and reducing reagent cost

CUSTOMER CHALLENGES
• Poor control of concentrate grade
• Lack of metal recovery control
• Excessive use of reagents

MPC BENEFITS
• Maintain concentrate grade to reduce product give-away or off-spec by 3%
• Increase metal recovery by 2%
• Reduce reagents by 3%
• Typical payback less than 1 year
Flotation column

MPC

OBJECTIVES

- Control concentrate grade (purity)
- Maximize metal recovery
- Control pH
- Control froth depth
- Control bubble speed or air hold-up
- Control bubble size distribution (BSD) or bubble surface area
- Maintain liberation in a range
- Control bias flow (water flowing down the column)
Optimization using model predictive control in mining

Flotation column matrix

<table>
<thead>
<tr>
<th></th>
<th>Maximize</th>
<th>Upper Constraint</th>
<th>Lower Constraint</th>
<th>Upper &amp; Lower Constraint</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>Collector reagent flow ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV</td>
<td>Depressor reagent flow ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV</td>
<td>Modifier reagent flow ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV</td>
<td>Tail flow</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV</td>
<td>Air flow</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV</td>
<td>Frother reagent flow ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV</td>
<td>P80 grinding</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MV</td>
<td>Wash Water flow ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DV</td>
<td>Feed flow-grinding</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DV</td>
<td>Feed density-grinding</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

OBJECTIVES

- Control concentrate grade (purity)
- Maximize metal recovery
- Control pH
- Control froth depth
- Control bubble speed or air hold-up
- Control bubble size distribution (BSD) or bubble surface area
- Maintain liberation in a range
- Control bias flow (water flowing down the column)

Maintain concentrate grade
3% reduced product give-away
3% reduced off-spec material
2% increased metal recovery
3% reduced reagents
Thickener
Model Predictive Control (MPC)

CUSTOMER CHALLENGES
• Fresh water availability and cost
• Reagent cost
• Existing conventional control is inefficient (long residence time, large disturbances and non-linear behavior)
• Thickener shutdown may stop all the production line

MPC BENEFITS
• Increase water recovery by 3% (typically 9,000 m³/day)
• Reduce flocculant by 2%
• Reduce possibility of emergency feed shutdown
• Typical payback less than 1 year
**OBJECTIVES**

- Maximize (or control) % solids (or density) in the mud
- Keep rake arm torque below a limit
- Keep mud pump amps below a limit
- Keep bed level in a range
- Keep water quality (turbidity) in a range
**Thickener matrix**

**OBJECTIVES**

- Maximize (or control) % solids (or density) in the mud
- Keep rake arm torque below a limit
- Keep mud pump amps below a limit
- Keep bed level in a range
- Keep water quality (turbidity) in a range

<table>
<thead>
<tr>
<th>MV</th>
<th>Mud bottom flow</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>Flocculant flow</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DV</td>
<td>Feed pH</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DV</td>
<td>Feed density</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DV</td>
<td>Feed flow</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

| CV | Bed pressure   |   |   |   |   |   |
| CV | Mud density    |   |   |   |   |   |
| CV | Rake arm torque|   |   |   |   |   |
| CV | Mud pump       |   |   |   |   |   |
| CV | Bed level      |   |   |   |   |   |
| CV | Water turbidity|   |   |   |   |   |

3% Increase in Water Recovery
2% Reduction in Flocculant
Avoid Feed Shut-down
Material flow management
MPC | Route optimization: Maximizing material throughput

CUSTOMER CHALLENGES

• Inconsistent production rates
• Loss of production at shift change
• Conveyor system trips

MPC BENEFITS

• Maximizing ore flow
• Operate to maximum constraints
• Minimize equipment trips
• Extending equipment life
• Minimize interruptions during shift changes
Material flow management

MPC

OBJECTIVES

- Maximizing ore flow
- Operate to maximum constraints
- Minimize equipment trips
- Extending equipment life
- Minimize interruptions during shift changes
Controller matrix

<table>
<thead>
<tr>
<th></th>
<th>CV1</th>
<th>CV2</th>
<th>CV3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MV2</td>
<td>NO MODEL</td>
<td></td>
<td>NO MODEL</td>
</tr>
<tr>
<td>MV3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DV1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DV2</td>
<td></td>
<td></td>
<td>NO MODEL</td>
</tr>
</tbody>
</table>

Controller consists of a matrix of process model pairs that explain **IMPORTANT INTERACTIONS** in the process.

**PREDICT** future values of the CVs by movement of all the MVs and DVs.

**PROACTIVE CONTROL** to coordinate MV setpoints to minimize CV deviations from targets, hence reducing variability.
Optimization using model predictive control in mining
How MPC generates benefits

- REDUCES Variability
- ACHIEVES ‘Plant Obedience’
- MANAGES the process within constraints
- ACHIEVES UPLIFT – operate closer to specifications and performance limits while maintaining safety margins
MODEL PREDICTIVE CONTROL

Solution for Flotation Cell at Latin American Iron Mine

PAVILON8 + VOA (VIRTUAL ONLINE ANALYZER)
STABILIZATION CONTROLLER & QUALITY AND RECOVERY
OPTIMIZER CONTROLLER

Non-Linear Advanced Process Control
FLOTATION CONTROL

Reduced product give-away and off-spec of 3% = 18,000 tonnes

3%
INCREASED METAL RECOVERY

2%
REDUCED REAGENTS

3%
REDUCED Product Give-away and Off-Spec
<table>
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<th>ACCESS</th>
<th>DELIVER</th>
<th>AUDIT</th>
<th>SUSTAIN</th>
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<td>• Propose and Plan</td>
<td>• Design, Develop, Deploy</td>
<td>• Commissioning</td>
<td>Value-Based Proposal</td>
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<td>• Confirm Business Value</td>
<td>• Data Gathering and Validation</td>
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<td>• Set Expectations</td>
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<td>• Determine Benchmark Metrics</td>
<td>• Application Deployment</td>
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**ValueFirst**
Level 1 Support

Email and live telephone support

MPC System recovery assistance from server failures

Service-Pack Releases provide updates and system changes
Level 1 and Level 2 Support

- Email and live telephone support
- MPC System recovery assistance from server failures
- Web-based Pavilion8 Support Knowledgebase and annual onsite visits available for APC
- Quarterly Pavilion8 MPC status reporting and troubleshooting APC application issues
- Service-Pack Releases provide updates and system changes
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<td>Included</td>
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<td>Remote or Onsite Available</td>
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Our sustained value services help protect your investment