Power Plant Controller (PPC)
for Grid-Connected Power Plants with Energy Storage
-
Product and Professional Services Offering

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1. Grid Connected Power Plants with Energy Storage

The scope of the current document is “grid-connected power plants with energy storage”. This could be a stand-alone energy storage system (e.g. for dispatched frequency regulation service), or it could be an energy storage system integrated into a photo-voltaic farm. The energy storage component is assumed to be a KW or MW scale energy storage device, typically a battery, which is connected via power electronics to the AC electric grid.

In a typical battery energy storage system (BESS) installation there are one or more channels, each comprised of power electronics (a “PCS”) and a battery. Each battery can be megawatt scale, and the combined system is able to provide or absorb dozens or hundreds of megawatts of power. The PCS converts power to or from the DC bus to 3-phase 480v AC, which is stepped up by an isolation transformer to a medium voltage AC “collector bus”. The collector bus accumulates power from all channels and is instrumented with a power meter at a “point of common coupling” (PCC).

The PCS is typically 4-quadrant capable, which means it can provide or absorb real power (KW), and can simultaneously provide or absorb reactive power (KVAR).

There is a great deal of excitement about battery energy storage in the electrical power industry because of widely recognized potential benefits it can offer. Some of the benefits are listed below:

- Intermittency mitigation in wind and PV plants
- Energy arbitrage
- Frequency regulation ancillary services
- Voltage regulation
- Power flow stability improvement

While these benefits are widely recognized in principle, many practical technologies need to be brought to maturity to scale these systems to an economically meaningful level. The power plant controller (PPC) is one such technology. While the benefits in principle of a BESS can be demonstrated without a PPC, it fills a necessary role in any full-scale BESS application. The role of the PPC is to provide a unified view of the large number of electronic devices in a full-scale BESS from both the perspective of instrumentation, control, and communication.

2. Background of IDI

Integrated Dynamics, Inc. (IDI) has been a supplier of specialty engineering consulting and software development services since 1997, being a domain expert in embedded device communication protocols, embedded controls, workflow, and methodologies. During the past seven years, IDI has developed domain and application expertise in controls for grid-connected energy storage, large-scale Lithium ion battery management, secure telemetry, large-scale historical data logging, and in engineering tools for process and workflow optimization.

Regarding Lithium-ion battery management systems (BMS), IDI has developed advanced BMS software, including state-of-charge (SOC) and state-of-health (SOH) estimation algorithms based on parameterized models of battery impedance and dynamic cell-voltage relaxation. In addition to SOC and SOH, the BMS incorporates diagnostics for cell protection (e.g. voltage and temperature), application integration (e.g. CAN interface, contactor control, application diagnostics). The BMS is designed to be configurable for small systems (e.g. 24 volts) up to large systems (e.g. 1000+ volts). IDI developed both the embedded BMS software, as well as high level PC-based GUI software such as a BMS Service Tool, a BMS Engineering Configuration tool, and a touch screen HMI for the BMS. The BMS we developed is used in megawatt scale grid connected applications, as well as transportation and other smaller scale applications.

IDI has also developed a purpose-built Power Plant Controller (PPC) for grid-connected battery energy storage (ESS) applications. The PPC is a special purpose supervisory control system for a site. The PPC contains subsystem-focused logic for integrated management of all subsystems within the ESS, as well as energy system-focused logic for application to the grid. For example, we've deployed grid-integration control strategies for primary frequency response, secondary frequency response (i.e. so-called AGC dispatching), power smoothing for integration with renewable power plants, and external control for integration with customer SCADA systems. The system was designed to integrate flexibly with multiple battery / inverter combinations, including mix-and-match configurations with multiple vendors, subsystem software versions, and various power and energy ratings. As with the BMS, the PPC system includes both the embedded software and a suite of related GUI tools to interact with it both locally and remotely over a network.

IDI lead the development of first and second generation PPCs (previously called the "Site Dispatch Controller") for a customer between 2009 and 2012, which were deployed at seven installations wordwide for a variety of applications. The first generation was built on PLC technology; the 2nd generation was built on an embedded industrial computer running the embedded Linux OS. The current product offering, which is being developed in-house at IDI, is a 3rd generation design that builds on the experience gained in development and deployment of the earlier systems.

In addition to battery and grid integration projects, IDI has extensive experience in automotive communication protocols (e.g. UDS on CAN, SAE J1939, SAE J1587, and several proprietary protocols), interface metadata standards (e.g. ODX, MDX, A2L, etc.), and has developed a sophisticated database-driven document generation system for legislated automotive OBD certification.

3. Terminology

Term	Definition
Battery Cell-Group	A battery cell-group is a collection of battery cells assembled permanently in parallel so that they act as a single cell with larger capacity. A cell-group has a single shared cell voltage at all times.
Battery String	A string is a series-connected collection of battery cell-groups.
Battery	A battery refers to one or more battery strings arranged in parallel. Multi-string batteries typically have separate voltage and temperature measurements on each string, and as well as DC contactors or breakers on each string, but are tied to a common DC bus after the contactor / breaker.
Battery Management System (BMS)	A battery management system is an electronic device used to monitor a battery's operation and to protect it from damage. The BMS provides a single point of interface between the battery and the PPC, even on multi-string batteries.
Power Conversion System (PCS)	A Power Conversion System (PCS) is an inverter and its associated controls, thermal management, and diagnostic systems. The PCS can contain a single inverter, or multiple inverters running in parallel on a single DC bus.
Channel	A channel refers to a single energy source / sink paired with a PCS. In battery energy storage systems, the energy source / sink is a battery. However, in the more general case it could also be a super-capacitor, flywheel, wind turbine, PV array, etc.
Multi-Channel system	A multi-channel system refers to an installation containing multiple channels connected to the AC bus at the point of common coupling.
Photo-Voltaic (PV) Array	A photo-voltaic array is an array of photo-voltaic cells connected in series and / or parallel to increase its DC power rating.
Energy Storage System (BESS)	An energy storage system is a single-channel or multi-channel system in which the energy source / sink on each channel is an energy storage device (e.g. battery, flywheel, supercapacitor).
Battery Energy Storage System (BESS)	A battery energy storage system is an energy storage system where the energy storage device is a battery.
Point of Common Coupling (PCC)	The point of common coupling is a point in the AC bus through which power from the entire ESS flows.
Auxiliary Service Computer (ASC)	The auxiliary service computer in the IDI PPC offering is a rack-mounted server which houses non-control features such as (a) Secure Remote Access, (b) Historical Data Logging, (c) Network Reachability Tool, and (d) Password Management System.
Diagnostic Trouble Code (DTC)	A diagnostic trouble code is a representation of an alarm or warning. Each DTC consists of (a) a source device, (b) numerical code, and (c) ASCII name.

4. Power Plant Controller

IDI is developing a generalized Power Plant Controller (PPC) for grid-connected energy storage applications. The PPC is designed to be cost effective for small installations, and is designed to scale well and be full-featured for large installations.

IDI's system is extensible to work seamlessly with multiple PCS vendors and versions, and multiple BMS vendors and versions. For example, a single installation can support one PCS version on channel #1, and a different PCS version, or even a different PCS vendor, on channel #2, etc. It is even possible to support dissimilar storage technologies (e.g. battery vs. flywheel, or different classes of batteries) on different channels within the same ESS. This is the kind of flexibility that is necessary in practice for large-scale systems which can be commissioned gradually over the course of years, and in which subsystems may eventually be decommissioned and replaced with equipment from competing vendors.

The PPC offering is based on a modular "product line" philosophy, in which the there is a core set of required features, an optional set of extended features, and software hooks for developing custom features which are project-specific or customer-specific (i.e. available to any of the customer's projects).

An interface to a new PCS, or a new version of an already supported PCS, is treated in the PPC framework like a customer-specific feature. Once implemented, the new feature (i.e. PCS interface) is available without further software development on any subsequent installations using the same PCS. The same applies to the BMS.

For each new project, IDI will examine the customer's project-specific needs and then recommend the best combination of extended features, previously-existing customer-specific features, and / or recommend developing new custom features.

4.1. Conceptual Control Architecture

The PPC software is organized at its core as a dispatcher for channels, most commonly energy storage channels. Behind the dispatching logic is a control-logic functional block that determines the overall closed-loop dynamics of the complete ESS as a whole.

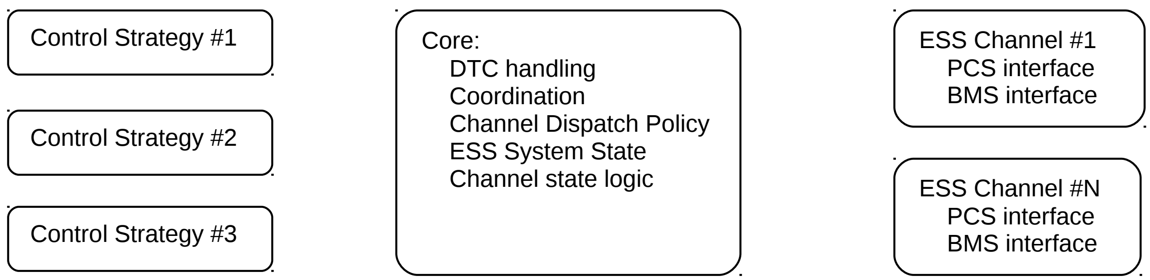

Figure 1 Block Diagram of Conceptual Control Architecture

A given installation will make available one or more control strategies. The operator can use the HMI to select which of the available control strategies to use for AUTO-mode operation.

IDI offers several pre-defined control strategies, as well as the option to develop custom control strategies for specific customers or specific projects. For example, the ESS may be installed as part of a PV power plant. In this case, there could be a need to create a custom control strategy which incorporates curtailment of the PV inverters in order to meet particular project-specific control objectives.

The output of the active control strategy feeds into the core dispatcher logic. This is where DTC's are handled, channel state is managed, and power commands allocated to channels.

The final state in the conceptual architecture is the channel interface. This is where channel-specific signals are mapped to I/O registers, depending on the configuration specifics for each channel.

4.2. Communications Architecture

The PPC is designed using TCP/IP as the transport for all internal communication. The PPC exchanges monitoring and control signals with the PCS controller in each channel. In some configurations it also exchanges monitoring and control signals with the BMS on each channel. Additionally, the PPC interfaces with site-level instrumentation such as a PCC-level power meter, PCC-level protection relay, and sometime external power meters which are used by the control strategy. Last, the PPC can interface to utility SCADA system.

In integrated renewable power plant installations, the PPC may communicate with PV inverters or wind inverters, with an external power-plant controller, or with power meters for other parts of the integrated power plant.

4.3. Software Architecture

IDI has designed the PPC software architecture to be flexible, with the following specific design objectives:

- Portable — Able to run on a variety of computing hardware platforms, to ensure the software remains relevant even has hardware evolves.
- Modular — No software component needs to be branched (separate copies, modified in separate revision control systems) in order to support the needs of multiple projects or customers.
- Configurable — Separates the software logic from the configuration. Has the ability to support multiple versions of PCS, BMS, and device interfaces via configuration, without needing to rebuild and retest the software.
- Performance — Minimizes the delay from a change on an PPC input until the change is dispatched to the PCS channels.
- Security — Follows IT industry best practices for secure networked communication where possible, subject to device compatibility requirements.
- Remote Access — Easy to securely monitor and operate remotely.
- Software QA — Minimizes release of defects to the field by following a methodical development process.

4.3.1. Portability

The PPC software is designed to operate on any modern embedded, desktop, or server distribution of the Linux operating system. Normally IDI chooses an embedded or server Linux distribution, rather than a desktop distribution, in order eliminate running processes which could cause stability or reliability of the system.

IDI selects the computing hardware for a given project based on the specific needs of the project, such as environmental requirements (e.g. humidity, temperature) and size of the installation (e.g. number of ESS channels).

Normally the configuration is chosen as one of the following:

- MOXA IA3341 or equiv — Small; fanless; ARM-based; embedded Linux; for applications not needing high performance computing.
- MOXA V2101 or equiv — Ruggedized; fanless; PC-class processor; Ubuntu 14.04 LTS Server (Linux); for applications needing high performance computing.

4.3.2. Modularity and Customization

The PPC software architecture has hooks for inclusion of custom features. A custom feature can be project specific – i.e. only available in the PPC software for the particular project – or it can be customer specific – i.e. available for any of the customer's projects.

The PPC software build for a given project would include IDI's core features, the extended IDI features selected for the project, plus any applicable customer-specific custom features, plus any project-specific custom features.

Example: Renewable Energy Power Plants
For example, suppose an ESS is to be installed in a solar PV farm to mitigate intermittency issues and to provide a direct response to grid frequency. In this case there may be value in having the PPC send curtailment commands to the PV inverters, and managed power from one or more diesel generators, in combination with commands dispatched to the ESS channels. The control logic for this application could be tailored as a project-specific custom control strategy.

4.3.3. Configurability

The PPC design uses an IDI-developed configuration management framework called "RDF", using a PC-based tool called the "RDF Engineering Tool". This tool enables flexible reconfiguration, such as choosing the number of ESS channels, and then choosing the type of each channel. For example, one ESS channel could be set up as PCS vendor #1 version 2; another ESS channel could be set up as PCS vendor #1 version 3; and yet another ESS channel could be set up as PCS vendor #2 version 5.

Different PCS version interfaces can be defined with different sets of diagnostics (i.e. Diagnostic trouble codes, or DTCs). Once a given PCS interface version is implemented, it can be used on any subsequent project via just a configuration setting.

Then within each channel, the rating of the channel can be configured. For example, channel #1 could have a maximum rating of {1200 kW, 1000 kVAR}, and channel #2 could have a maximum rating of {400 kW, 600 kVAR}.

The same kind of configurability applies to BMS interfaces, external device interfaces (e.g. power meters), and even control strategies.

4.3.4. Communication Performance

IDI's PPC is designed to minimize the delay from input to output. For example, if an input register changes, the PPC can immediately compute its effect on channel power commands and perform the corresponding Modbus TCP writes. This is in contrast to a fixed scan-rate design, which would compute the updates at a fixed pre-defined rate, and implements Modbus write operations at a fixed pre-defined rate. This approach minimizes delays. For example, the delay from reading an input register until the resulting PCS dispatch is written via Modbus TCP is less than 3 milliseconds when running on a higher performance computing platform, and is under 10 milliseconds when running on a lower performance computing platform.

4.3.5. Network Security

The PPC is designed with the utmost respect for network security issues. It does this by checking passwords on local and remote HMI connections. Of course, a network is only as secure as its weakest link, so the PPC's security precautions do not in themselves guarantee the system secure.

IDI offers professional services to assist the integrator in evaluating and improving security issues with the rest of the system (See section 7.3).

4.3.6. Remote Access

The PPC is designed to be remotely accessible. Remote access lowers support costs and improves ESS availability by ensuring that issues can be identified and remedied quickly and efficiently. Additionally, the design enables historical data logs to be accessed remotely within minutes, for rapid insight into the performance of systems in the field.

4.3.7. Software Quality Assurance

IDI employs an approach to software quality assurance with roots in automotive control systems, where rock-solid reliability matters. The QA process is as follows:

- (a) Requirements are carefully evaluated, documented, and reviewed with stakeholders
- (b) Software architecture is carefully designed and protected from degradation over time
- (c) Changes are carefully allocated to the appropriate location within the software architecture
- (d) A bench-test environment is configured to represent the project's interfaces and settings
- (e) Software changes are implemented and thoroughly bench tested
- (f) Bench test configurations and procedures are documented and archived
- (g) Finally, changes are released to the field.

IDI maintains a configurable bench test environment which can be reconfigured in very short order to replicate bench tests performed for any installation for which there is a current support contract.

We hold that, while a rigorous development process doesn't push changes into the field as quickly as an ad-hoc process, it achieves a mature solution faster and with fewer fielded defects.

It is also true, however, that in some cases the requirements are not well-understood ahead of time, and that rapid prototyping in the field can be benefiicial to application engineers.

4.4. Core Features

4.4.1. Base Control Logic

The PPC's base control logic manages the operating mode of each ESS channel. The operating mode is one of the following:

- **OFF_GRID** The channel is disconnected from the grid.
- **REMOTE** The channel is acting on P (real power) and Q (reactive power) commands from the PPC.
- **LOCAL** The channel is operating independently of the PPC.

These are the operating modes from the perspective of the ESS channel. The PPC operator, however, has another option: For ESS channels in REMOTE mode, the PPC can internally compute the channel commands either from manual commands (i.e. from the HMI or from remotely operating scripts), or from an active control strategy. The PPC manages the operating state of the channel.

4.4.2. Diagnostics Coordination and Reporting

The PPC reads the state of diagnostics from the ESS channel (PCS and / or BMS) and reports them to the user as diagnostic trouble codes (DTCs). Each DTC is pre-defined to have one of the following levels: { WARNING, DERATE, DISCONNECT }. WARNING-level DTCs are enunciated only for the information of the operator, but have no effect on system operation. DERATE-level DTCs indicate the system has reduced its power rating because of the active DTC. DISCONNECT-level DTCs indicate the system or sub-system (e.g. ESS channel) has disconnected from the grid.

A DISCONNECT-level DTC at a subsystem level may result in a DERATE level behavior at a system level. For example, if the PCS contains two inverter stacks, a failure that causes one inverter stack to go off grid may have no effect on the 2nd inverter stack. In this case, the ESS channel goes into a DERATE state, while the inverter stack is in a DISCONNECT state.

The same is true at the system level. A DISCONNECT-level state on one ESS channel will cause that channel to go off grid, but if there are other ESS channels that are on-grid, the system level effect is a system DERATE.

The PPC reports the DTCs that are active, and manages the aggregation of DTC levels to determine the overall system diagnostic level.

The PPC can be configured to latch a DTC-driven disconnect, or to automatically recover if a DTC is cleared. If configured to latch a DTC-driven disconnect, the system will require manual intervention to put the system back on-grid once it disconnects due to a DTC. The same configuration options are available on a channel-by-channel basis; that is, if an ESS channel goes off-grid because of DTC, the PPC can be configured to require manual interface to take that channel back on-grid after the DTC is cleared, or to enable the channel to go back on-grid automatically when the DTC is cleared.

The PPC provides a unified view of diagnostics to the user. In other words, although each subsystem (e.g. PCS, BMS, power meter, etc.) has its own representation of diagnostics, the operator sees a unified view, where all diagnostics are reported as DTCs with a symbolic name and description. In this way it is not necessary for operators to understand the nuances of different vendors' representations of diagnostics.

4.4.3. Channel Interface

The PPC defines a baseline conceptual interface to the ESS channel. The baseline interface defines a minimum set of information that must pass from the channel to the PPC, and a minimum set of information that must pass from the PPC to the channel.

The "channel" is a combination of a PCS and a storage technology (e.g. battery, flywheel). The minimum set of information listed above is for the "channel"; i.e. it is combination of PCS and energy storage system data. In some applications, a single device external to the PPC will aggregate the channel information (e.g. a PCS which communicates directly to a BMS), and in some cases the PPC will communicate directly to the PCS and BMS, and will therefore aggregate the information internally. Either way, the "channel interface" is the core concept on which the PPC architecture is based.

The minimum set of information from the channel to the PPC contains:

- PCS operating mode
- PCS DTC accommodation level
- List of active PCS DTCs
- Real and reactive power limits of the PCS (oval shape limits)
- Actual real and reactive power measurements
- Actual 3-phase voltages and currents
- Storage device operating mode
- Storage device DTC accommodation level
- List of active storage device DTCs
- Real power limits (straight line limits, independent of reactive power)
- Storage device state of charge (%)

The minimum set of information from the PPC to the channel contains:

- Commanded channel operating mode
- Commanded real and reactive power
- PCS DTC-reset command
- Storage device DTC-reset command.

Note that the abstract "channel" concept is agnostic regarding the energy storage technology (e.g. battery, flywheel, supercapacitor). If the storage device is a battery, then the corresponding information comes from a BMS.

The interface to a practical PCS or BMS will involve information in addition to the minimum set. The additional information is for display on an HMI or for data logging purposes. Such additional information will be part of the PCS type-specific interface. The register mapping for different types of PCS interfaces will be different; the PPC's control logic and diagnostic management functions, however, are independent of the way the minimum set of signals are mapped to registers.

The purpose of the PPC is operation, which is distinct from data logging. Typical systems have a very large number of internal signals (e.g. individual cell voltages and temperature) which can be monitored and logged for data analysis purposes, but which are not needed for operational purposes. Such signals are not used by the PPC, but are instead handled by the Historical Data Logging feature, which runs on different computing hardware. (See section 4.5.3).

4.4.4. Power Meter Interface

The PPC has a baseline conceptual interface to a power meter. The baseline interface defines a minimum set of information that must pass from the power meter to the PPC:

- Real power
- Reactive power
- Phase AB Voltage
- Phase BC Voltage
- Phase CA Voltage
- Phase A Current
- Phase B Current
- Phase C Current
- Power Factor

Interfaces to specific power meters may also be augmented with additional information. The register mapping for any particular type of power meter will be unique to that meter. Once a given type of power meter is defined in the system, it can be configured on any subsequent project using the RDF Configuration Tool, without requiring software development.

4.4.5. Human Machine Interface (HMI) Software

There is an HMI software application which interfaces to the PPC. The same HMI software can communicate with any installation. The HMI is designed to recognize and adapt to the configurations of specific installations. For example, if one site has just one ESS channel, the HMI will only show one channel when connected to that site. Suppose another site has ten (10) ESS channels, some of which have two inverter stacks and some of which have one inverter stack. If the HMI is connected to this more complicated site, showing a screen with inverter stack operating information, then the HMI will show the information relevant to the ESS channel it's displaying. This means event the layout on the screen can be different for different ESS channels.

If an integrator or operator supports multiple installations, it is convenient for the user to be shown the correct information for the specifically connected site, rather than requiring the user to choose a different HMI program for different sites.

If the site supports Secure Remote Access, the same HMI can connect to the site via a secure communication channel for real-time monitor and / or control.

The HMI software requires Java, and can operate on Windows 7, Windows 8, Linux, etc.

If a permanent on-site HMI workstation is desired, the system integrator can install the HMI software on a standard Windows PC located at the site. The standard PPC offering, therefore, does not include a PC for running the HMI.

Screen snapshots of the HMI connected to a PPC running in a controller-in-the-loop bench test environment are shown in Figure 2 through Figure 8.

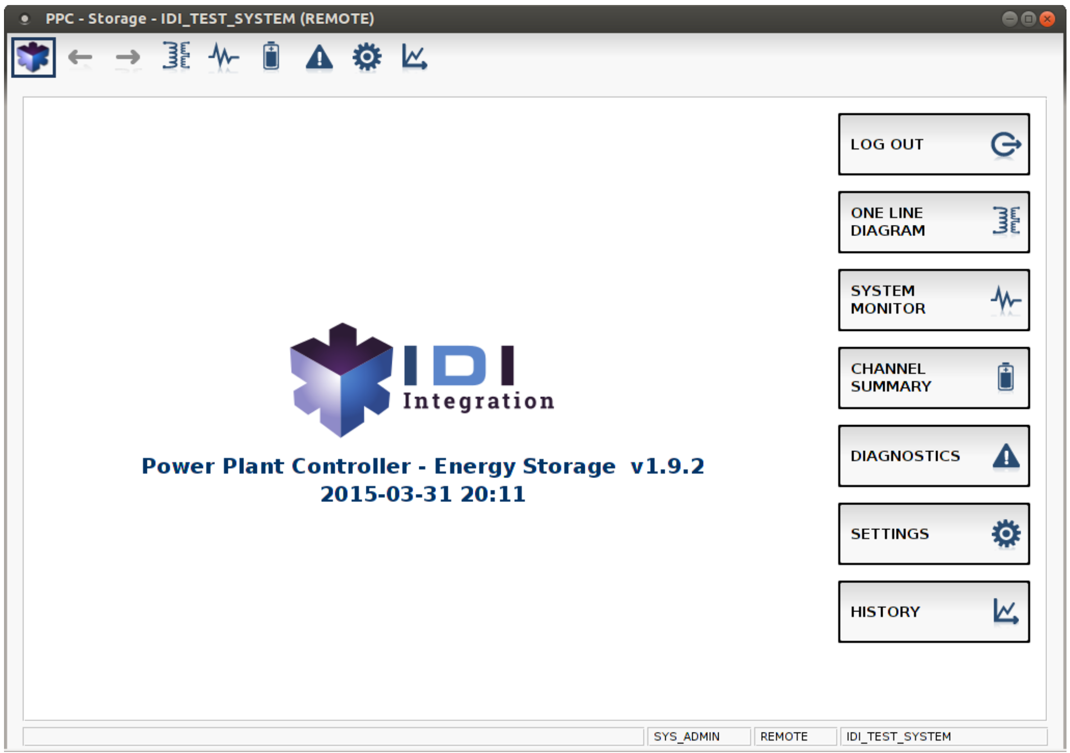

Figure 2: HMI screen snapshot – Home screen. The UI is “skinnable” – that is, the customer's logo, color scheme, and icons can be used.

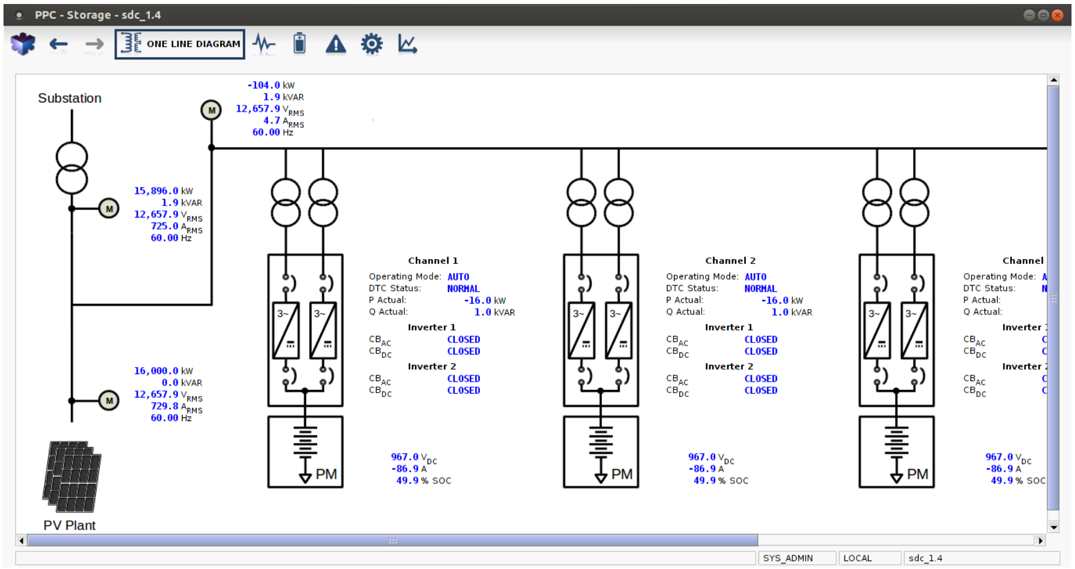

Figure 3: HMI screen snapshot - One line diagram screen

Figure 4: HMI screen snapshot - System monitor screen

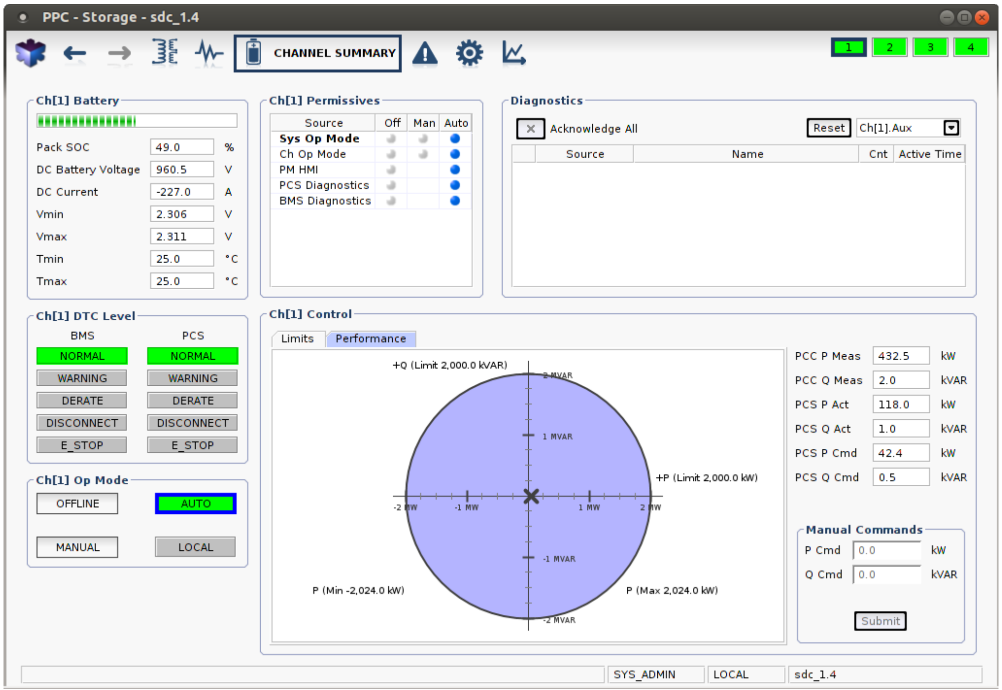

Figure 5: HMI screen snapshot - Channel summary screen

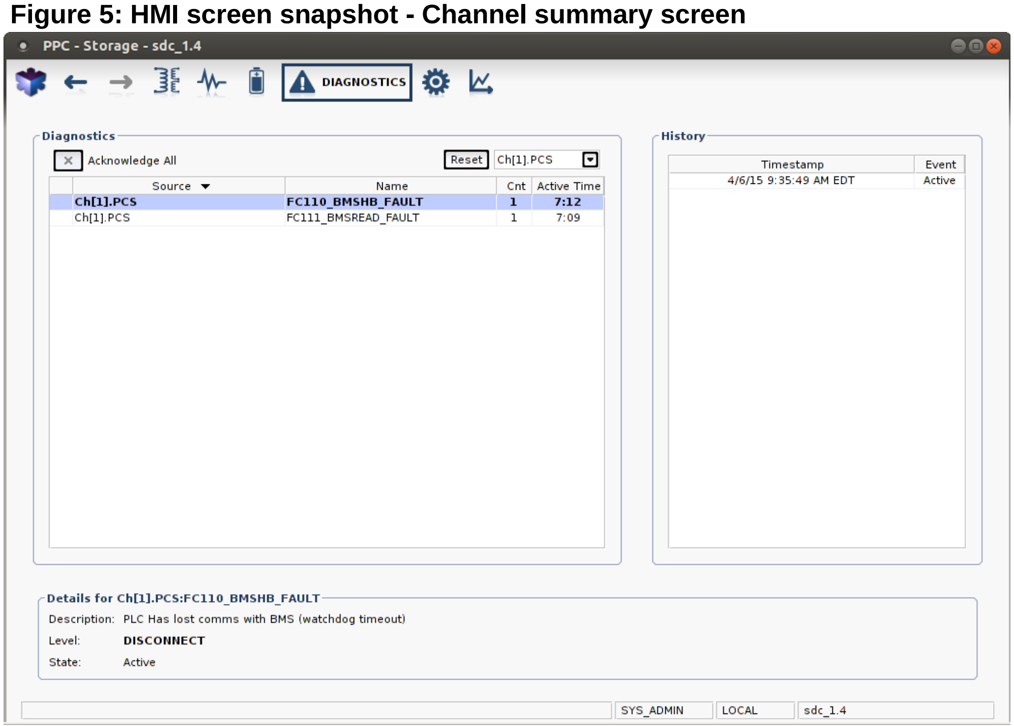

Figure 6: HMI screen snapshot - Diagnostics screen

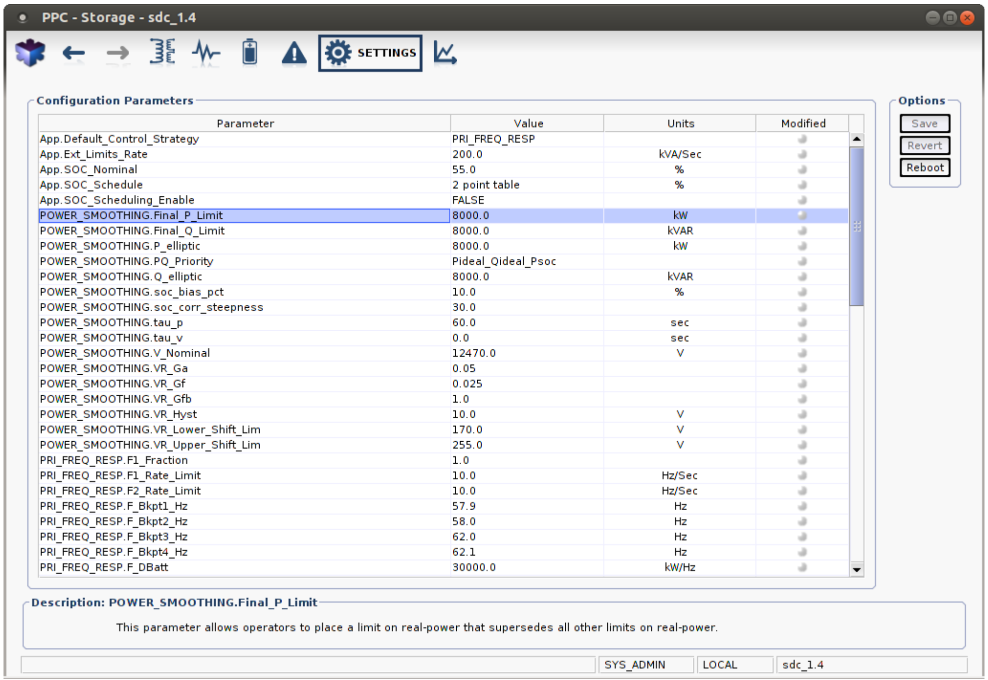

Figure 7: HMI screen snapshot - Settings screen

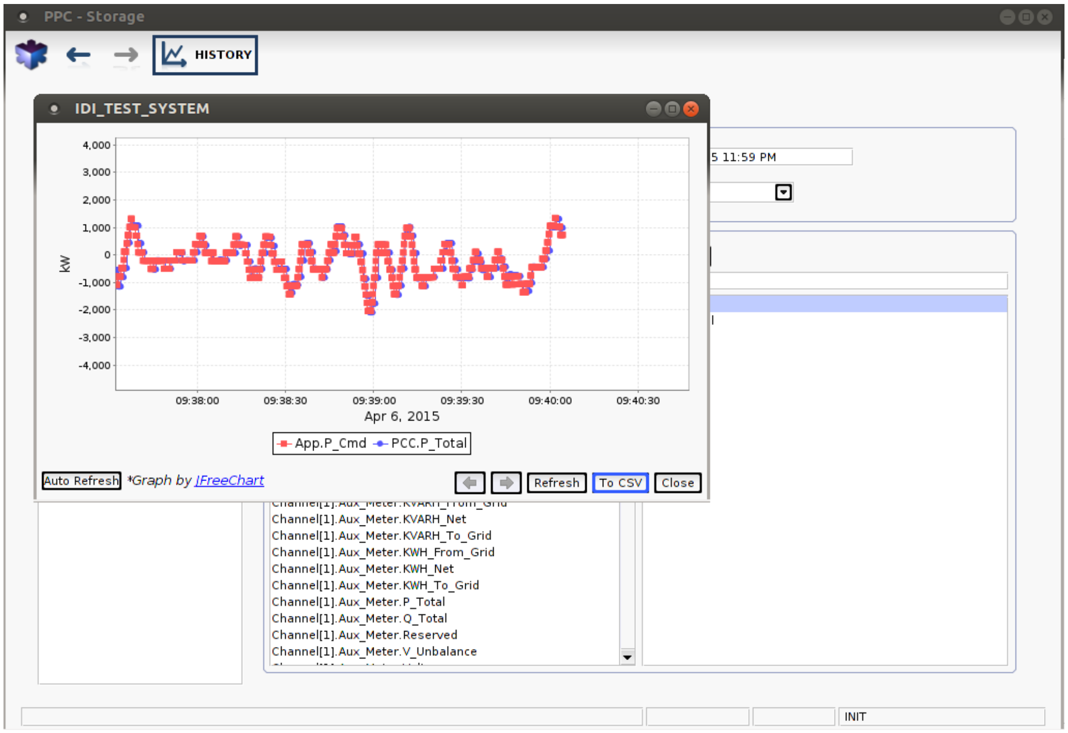

Figure 8: HMI screen snapshot - History screen

4.4.6. Selectable Control Strategy

The PPC's software architecture contains an abstract block called its “Control Strategy”. The Control Strategy block can be configured to use a built-in control strategy, a project-specific custom control strategy, or a customer-specific custom control strategy (which would then be available for use on any of the customer's projects).

Each control strategy employs some kind of logic to compute real and reactive power commands that can then be dispatched to the AUTO-mode ESS channels.

A given PPC can be configured at project build time to support any number of control strategies. At run time, the operator of the HMI could then select which of the supported control strategies to use, or to disable AUTO-mode altogether.

4.4.7. Transformer Loss Compensation

The PPC estimates losses in the step-up transformer(s) between the PCS and the MV collector bus. This estimated loss is added to the desired ESS output power from the active Control Strategy to obtain the power command to be dispatched to the ESS channels.

4.4.8. External Curtailment

The PPC has curtailment limits that can be set by a remote system. The curtailment limits act basically as reduced limits applied to the ESS site as a whole. The limits are:

- `P_max_ext` Maximum real power output, independent of reactive powe

- `P_min_ext` Minimum real power output, independent of reactive power
- `P_limit_ext` Real power radius of 4-quadrant oval limit
- `Q_limit_ext` Reactive power radius of 4-quadrant oval limit

These limits apply to the entire site, restricting the sum of MANUAL-mode and AUTO-mode channels.

The limits can be mapped to registers which are writable by a remote system (e.g. Modbus TCP server, DNP3 server).

4.4.9. Protocol Support: Modbus TCP

Out of the box the PPC supports Modbus TCP. The PPC can be a Modbus TCP master (i.e. initiates requests to other devices) or slave (processes requests from other devices). In a typical ESS configuration, the PPC is the master for communication with other devices within the system, but is a slave for communication with external devices (e.g. a customer control or monitoring system).

The PPC's Modbus TCP implementation is able to restrict which IP addresses can connect for reading, which can connect for writing specific registers. For example, one IP address may be allowed to write to one group of registers, and another IP address may be allowed to write to a different group of registers.

While Modbus TCP is an open protocol that doesn't have built-in strong security, this restriction by IP address provides a measure of security not available in entry-level devices.

4.5. Extended Features

4.5.1. Network Reachability Tool [Roadmap]

The recommended network topology for a multi-channel ESS system is to use identical LAN segments in each ESS channel. For example, every PLC controller will have the same IP address, and every PCS HMI computer will have the same IP address. This makes development and testing of the channel building blocks more straightforward than having separate IP addresses for all devices in the system.

It means, however, that each ESS channel needs a NAT router to interface between the channel and the PPC. The NAT router's external IP address (i.e. "WAN-side") would be channel specific, but its internal IP address (i.e. "LAN-side") would be the same on every channel (e.g. 192.168.1.1).

With this kind of network topology, devices behind the channel's NAT router are not directly reachable by IP address. Therefore, in order to have low-level network access to such devices, the network connection must be tunneled through a port-forward channel. A common device for this kind of tunneling is SSH port forwarding.

The Network Reachability Tool is a means to perform port forwarding to enable connectivity from the system's primary network to the devices behind the channel NAT routers. The tool is installed on the Auxiliary Services Computer (ASC).

4.5.2. Secure Remote Access

And extended feature offered in conjunction with the PPC is Secure Remote Access. There are two levels of Secure Remote Access:

- **Level 1** – HMI — The HMI can be connected to the PPC securely over a remote network connection.
- **Level 2** – Port Forwarding. — Generalized low-level communication can be enabled by TCP port-forwarding between the user's PC and the site.

The Secure Remote Access service runs on the Auxiliary Services Computer (ASC); it opens an encrypted connection with a service running in the cloud to register its availability.

When Level 1 is enabled, the user can then open a connection to the remote site using the HMI, which in this case runs on the user's personal computer. The HMI connects to the cloud server via its own encrypted connection; the cloud server then relays messages between the HMI and the PPC.

When Level 2 is enabled, the Secure Remote Access system allows connectivity to any networked device that's reachable from the system's primary network, albeit using low level networking tools, not using the HMI application. For example, suppose a Shark 200 power meter is reachable from the primary network. Then the Electro Industries "Communicator Ext" software package can be run on the user's PC, and connected via the encrypted cloud server connection to the Shark 200 located at the site.

If the Network Reachability Tool is used for the site and Level 2 Secure Remote access is enabled, then any device in the entire ESS can be reached remotely.

Level 2 Secure Remote Access is suitable for a trained engineer or technician, but is not normally appropriate for an end-user operator.

4.5.3. Historical Data Logging – Cloud Based

If the Historical Data Logging feature is used, detailed signals from all channels can be logged to a historical database, for post processing and analysis. The Historical Data Logging service runs on the Auxiliary Services Computer (ASC).

A bewildering number of signals are available for logging in a large system. For example, suppose each battery in a multi-channel system has 300 cell voltages and 100 temperatures, and suppose there are 50 such channels. These alone, excluding inverter signals and power commands and measurements, represent 20,000 signals. Including other signals, a realistic number for a 50 channel system is over 25,000 signals in total. If all these signals are configured to for logging once per second, the historical data log would write 25,000 data points per second continuously. This would accumulate at the rate of 2 billion data points per day. If the storage for this information requires 2 bytes per data point, this will accumulate approximate 128 GB per month. For this reason, the Historical Data Logging service runs on the ASC rather than on the PPC in order to separate the high-volume data storage system from the real-time controls.

In practice, temperatures generally change much more slowly than voltages. In general, different signals should be sampled at different rates, based on its typical rate of change.

The remote HMI provides convenient graphical access to logged data as a time series plot. A programmatic interface to historical data is provided for detailed quantitative analysis.

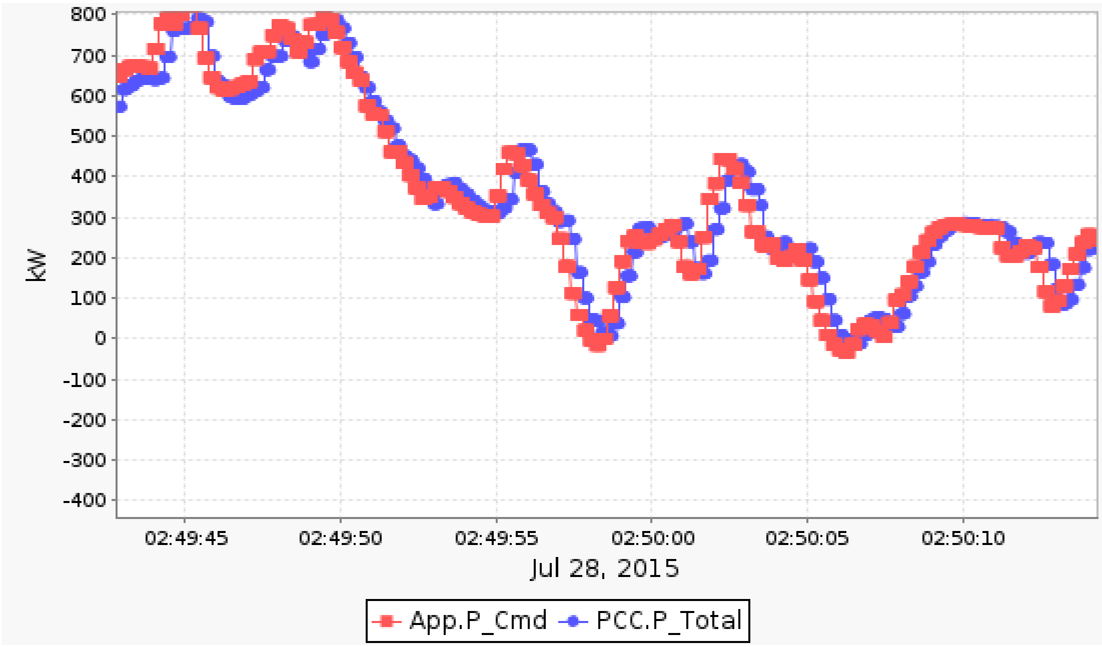

Figure 9: Example plot of historical data

The IDI historical data logging system requires caches log data locally on site, and then periodically pushes the data to a cloud-based server over the Secure Remote Access connection. The typical period for pushing data to the cloud is every five (5) minutes. Users access the data by querying and analyzing data from the cloud server.

If the site does not have Secure Remote Access, or if remote access is temporarily down for technical reasons, the logging data accumulates in the site's data cache, up to a configurable limit based on the size of the site. The amount of cache space available, and the length of time until it is full, causing old data to be discarded, depends on sampling rates and other parameters set up for the site. In this case, a technician can later synchronize the data with the cloud server, transferring the data temporarily to the PC, and from the PC to the cloud server.

4.5.4. Historical Data Logging – On-Site

The same LTS historical data logging system which IDI runs on our managed cloud server can alternatively be installed on-site on the ASC. This arrangement provides the same logging of data, but requires remote access to the site in order to retrieve and analyze the data.

4.5.5. Redundancy with Automatic Failover [Roadmap]

The PPC's operation is critical to an ESS installation. Without a PPC, the installation must go off-grid. To support high availability, IDI's PPC can be operated in a redundant configuration. With this feature, the auxiliary services computer (ASC) can run as a backup PPC if the primary PPC fails. The PPC and

ASC (backup PPC) are powered by separate power supplies, and connected to the network via separate routers.

The PPC is designated as 'primary', and the backup PPC (i.e. ASC) is designated as 'backup'. The primary PPC transmits a 'heartbeat' signal to the backup PPC. The backup PPC passively listens to the heartbeat signal. If the heartbeat signal stops, the backup PPC immediately begins sending commands to the ESS channels to keep them from timing out and going off-grid.

In order to prevent possible interference with real-time control, the Historical Data Logging feature, which also runs on the ASC, is disabled while the backup PPC service is active.
Once the primary PPC is restarted, it exchanges a handshake with the backup PPC, signaling the intention to resume normal operation. In response the backup PPC stops its control operation, after which the primary PPC again takes control of the site, and Historical Data Logging resumes.

NOTE: Failover can occur quickly enough to prevent the ESS channels from timing out and going off-grid, but in some cases the system will experience a short-duration change in output power. That is, the PCS power commands in many cases will experience a transient "blip" when the failover event occurs, with a quick but not instantaneous recovery.

Additionally, if the ASC fails, since it normally runs the Secure Remote Access service, remote access would be at risk. To prevent loss of access, there is a backup Secure Remote Access service that runs on the PPC. It connects to the cloud server in case of failure of the ASC.

NOTE: The failover feature would normally be used in conjunction with PRP/HSR network redundancy. See 7.1 regarding network redundancy.

4.5.6. Redundancy with Manual Failover

An alternative to Automatic Failover is to have redundant PPCs with the ability to manually switch between them. If a hardware failure occurs in the PPC, service personnel can manually switch to the backup PPC. This reduces downtime associated with PPC hardware failure, but does not require the software complexity that full automatic failover entails.

4.5.7. Multi-Channel Coordination

In a multi-channel ESS, there is a need for coordination among the channels. The need for coordination occurs both in auto-mode (i.e. while running the entire ESS with an active control strategy), and in manual-mode (i.e. while operating one or more channels based on manual commands.

<u>Channel Enable / Disable</u>

It is possible to disable an ESS channel when it is entirely unavailable, such as when the PCS is out of service, or before it is installed. When a channel is disabled, there will be no DTC for loss of communication with the channel. This is particularly useful when gradually installing a large multi-channel site over long periods of time. The PPC would be configured for the full system, but the channels would be enabled only as they are brought online and commissioned.

<u>Power Limit Enforcement</u>

Different ESS channels will in general have different power limits, either by design, or because of derated operation. That is, an ESS system may by design have some channels with different ratings than others. Also, if a failure occurs on a channel normally having the same power rating as the others, then that channel may operate on a derated basis. In any case, the PPC will never command a given channel to a power level higher than its reported limits. This may force the PPC to adjust the power command dispatched to other channels to achieve the desired total power.

This limit-aware dispatching applies to both real power and reactive power.

Channel SOC Balance

If one channel is taken offline for a period of time for maintenance or repair, it's battery will hold a constant state-of-charge (SOC), while the other channels continue to operate under automatic control. When this channel resumes automatic control operation, the PPC will act to bring the SOC of all channels back into balance. For example, if one channel's SOC is below the average, the PPC will bias its auto-mode real power command toward charging, and if its SOC is above the average, the PPC will bias its auto-mode real power command toward discharging.

Manual Mode Compensation

It is possible to operate one or more channels in MANUAL mode (i.e. channel power command entered manually using an HMI), even while other channels are running in AUTO model. The PPC has a configurable setting for how the AUTO-mode dispatching should compensate for the MANUAL mode channel(s):

- Option 1 – Invisible at the PCC

  With this option, the MANUAL channel commands are subtracted from the desired total AUTO-mode power before dispatching. Then, when measured at the PCC, the total site power output will be what was computed by the AUTO-mode control strategy, hence making the MANUAL mode channel invisible when looking at PCC power.

  When operating with this option, the MANUAL mode channel's output may be automatically curtailed based on the AUTO-mode control strategy's power command. Suppose, for example, in a two (2) channel system each rated at 1000 kW, one channel is running in AUTO-mode and the other is running in MANUAL mode. Suppose the control strategy is calling for a total of +800 kW. Since the AUTO-mode channel cannot produce more than 1000 kW, the MANUAL-mode channel must be curtailed to no less than -200 kW; otherwise the sum of +800 kW would not be reachable.

- Option 2 – Visible at the PCC

  With this option, the AUTO-mode channels are dispatched as though the MANUAL mode channels were off-grid. Then, when measured at the PCC, the total site power will be the sum of the full AUTO-mode command, as computed by the control strategy, and the MANUAL.

4.5.8. Protocol Support: DNP3 over TCP/IP [Roadmap]

If this feature is selected, the PPC can act as a DNP3 outstation for interfacing with an RTU or SCADA system. The signals to be mapped to DNP3 can be configured on a project-by-project basis. Initially standard DNP3 will be supported.

Support for Secure DNP3 can be implemented in the future if required to satisfy customer needs. Similarly, the eventual need for the PPC can act as a DNP3 master for interfacing to devices is anticipated and will be implemented if required to satisfy customer need.

4.5.9. Protocol Support: IEC 61850 over TCP/IP [Roadmap]

The PPC is designed to be flexible extending support to multiple protocols operating over TCP/IP. The eventual need for IEC 61850 support is anticipated and can be implement as required to satisfy customer need.

4.5.10. Protocol Support: IEEE C37.118 Synchrophasors [Roadmap]

The PPC is designed to support the IEEE C37.118 standard protocol for synchrophasor measurements from compatible power meters and relays. A synchrophasor meter can be used in place of other meters, or it can be used for control strategies based on absolute phase angle.

4.5.11. Protocol Support: OPC UA

OPC UA is a well-known communication protocol which can be used for interfacing the PPC with a SCADA system. This feature reduces configuration complexity compared with Modbus TCP, but at the expense of being a more sophisticated protocol.

4.5.12. Password Management System [Roadmap]

Part of NERC CIP compliance is the ability to manage passwords, to control access to devices. We anticipate the eventual need for an installation password management system, or compatibility with a customer's internal password management system.

Since the detailed customer need for this is still ambiguous, nothing specific will be available with the initial product offering, but some kind of tool or capability will eventually be incorporated as customer needs arise and are clarified.

4.5.13. Energy Shift Schedule

The PPC can be configured to automatically absorb energy for part of a day and automatically release energy back to the grid for part of a day. To use this control strategy, the operator configures a schedule of reference SOC vs. time of day, and the PPC uses the active control strategy to drive the ESS toward the reference SOC.

4.5.14. External Script Execution [Roadmap]

The Script Execution feature is a service that runs on the Auxiliary Services Computer (ASC). The service has a scripting language which can be used to send commands to the PPC as though an operator had sent them from an HMI.

The operator can list, upload, delete, start, and stop scripts via the HMI. Only one script can be run at a time.

4.5.15. Ctrl Strategy – External P/Q Command

The PPC has an interface to an external controller, in which the external controller can send real and reactive power commands to the ESS. This is called a control strategy, even though it is just a signal pass-through, because it is a selectable alternative to closed-loop control strategies, so architecturally it plays the role of a control strategy.

The outputs (PPC → external controller) of the interface are:

- P_Limit — Real power radius of oval kVA limit
- Q_Limit — Reactive power radius of oval kVA limit
- P_Max — Maximum real power (independent of kVAR)
- P_Min — Minimum real power (independent of kVAR)
- SOC — ESS state of charge
- E_capacity — ESS nominal energy capacity of AUTO-mode channels
- ESS_state — Operating state
- DTC_Level — Cumulative DTC accommodation level of the ESS
- Active DTCs — List of DTCs currently active

The inputs (external controller → PPC) of the interface are:

- P_cmd_ext — Commanded real power
- Q_cmd_ext — Commanded reactive power
- ESS_state_ext — Desired operating state
- DTC_reset — Command to reset DTCs

This interface can be mapped to registers over Modbus TCP server, DNP3 server, etc.

4.5.16. Ctrl Strategy – PJM AGC Ancillary Service

The PPC can provide an interface to PJM's AGC system. This enables the ESS to participate in the PJM regulation ancillary service market. The PPC's inputs on this interface are:

- `PJM_AReg` — Assigned regulation (kW).
- `PJM_P_Cmd` — Regulation power command (kW) – "REGD" or "REGA".

The PPC's outputs on this interface are:

- `P_Range_Nominal` — ESS's nominal range of power (kW, symmetric between charge power and discharge power). The owner can using this quantity in combination with other dispatchable resources to compute the PJM "TREG" signal.
- `P_Actual` — ESS's real power output measurement (kW) at the point of common coupling.

The control strategy has the ability to compensate for SOC drift, and the relevant signals can be mapped to registers over Modbus TCP server or DNP3 server.

4.5.17. Ctrl Strategy – Hz / Watts Response

The PPC can be configured to respond directly to measured grid frequency. When operating with this control strategy, it retrieves grid frequency from a power meter and computes a real power command (kW) using a lookup table that maps Hz to Watts.

The control strategy has the ability to compensate for SOC drift, and has other factors (e.g. hysteresis / deadband) for a sophisticated dynamic response that can be tuned by a controls engineer for the specific application.

4.5.18. Ctrl Strategy – Volt / VAR Response

The PPC can be configured to respond directly to measured grid voltage. When operating with this control strategy, it retrieves grid voltage from a power meter and computes the reactive power command (kVAR) using a looking table from Volts to VAR.

The control strategy has the ability to compensate for SOC drift, and other factors for a sophisticated dynamic response that can be tuned by a controls engineer to the specific application.

4.5.19. Ctrl Strategy – Power Smoothing

The PPC can be configured to respond directly to an external power measurement from an intermittent power source or load, such as a wind farm or PV plant. With this control strategy, the combined power of the ESS and the external source / load has reduced short-term variability. When operating with this control strategy, the PPC is configured to point to an external power meter to use as its reference for smoothing.

The control strategy has several tunable parameters for a sophisticated dynamic response that can be tuned by a controls engineer to the specific application.

4.5.20. Ctrl Strategy – Composite [Roadmap]

The PPC can be configured to use a combination of other control strategies supported for the project. The combination is the sum of the power commands from the separate control strategies. If the sum lies outside the power limits of the ESS, the conflict will be resolved on a priority basis.

As an example how this might be used, consider an installation where primary frequency response and voltage regulation are both of interest, but where voltage regulation is higher priority. In this case, the installation could use the Composite control strategy configured with inputs from Volt / VAR Response and Hz / Watts Response. Since Hz / Watts Response is a real-power control strategy, and the Volt / VAR Response is a reactive-power control strategy, the sum would combine real and reactive power. If the combined real & reactive commands result in a kVA value that lies outside the ESS capability, the Volt / VAR output would be retained in full, and the Hz / Watt output would be reduced in magnitude such that the total falls within the ESS capability.

4.5.21. Ctrl Strategy – Customer Programmable Script [Roadmap]

The PPC can be configured to compute P and Q commands (real and reactive power) from a script that is written / maintained by the customer's application engineer. The script runs in the PPC's real time control system at a fixed execution rate, or when its inputs change, depending on configuration.

This puts the customer in control of the overall system operation, without requiring IDI to be involved in every change, and without requiring the application engineer to have software engineering expertise in the low-level functions of the PPC.

4.5.22. Modbus TCP Proxy [Roadmap]

In some cases a customer's application will need access to data from many different controllers. For example, it may need BMS information from each channel. The SCADA system may need access to data that is not required for the PPC function.

The Modbus TCP Proxy is a Modbus TCP server that maps different register address ranges to separate devices. For example, registers 1 through 100 could be mapped to BMS #1, registers 101 through 200 could be mapped to BMS #2, etc. The mapping is completely flexible, and requires very little configuration effort.

5. Support

The base product price includes product support for one year following delivery of the product. In subsequent years there is an annual fee for product support. Product support includes free bug-fixes for built-in features, access to the HMI for up to five (5) users, access to the cloud-based historical data log for up to five (5) users, and replacement or refurbishment of PPC or ASC hardware in case of failure.

IDI's standard support does not include on-site work. If PPC or ASC hardware fails while under a paid support contract, the customer will be required to ship the failed hardware to IDI's offices. IDI will refurbish or replace the failed hardware, configure it for the site, and ship it back to the customer, who will install it.

If the site is reconfigured after initial installation or other changes are made that require reconfiguration of the PPC and related features, IDI will make the required changes under the banner of professional services.

If on-site work is required, special arrangements can be made under the banner of professional services. IDI also offers professional services to support bug-fixes, enhancements, and phone and email support for functionality related to custom-developed features.

6. Deliverables

The PPC offering consists of the following itemized deliverables, depending on options selected:

- PPC computing hardware – primary, pre-configured with software for specific project
- PPC computing hardware – backup, pre-configured with software for specific project
- ASC computing hardware, pre-configured with software for specific project
- Wiring diagrams
- Installation and Operation Manual – General
- Documentation of custom-developed PPC features
- DTC spreadsheet for the PPC configuration delivered

7. Professional Services

IDI offers professional services to assist the customer in defining requirements, evaluating and recommending network topologies, reviewing diagnostics, selecting and configuring instrumentation, recommending procedures and mechanisms to achieve NERC CIP compliance, etc. as sometimes these are not well-understood at project inception.

7.1. Network Topology and Configuration

IDI offers professional services to work with the integrator to identify the needs and subsequently select and configure the network devices for the specific installation.

In all multi-channel cases, we recommend each ESS channel be a standalone network segment, separated by a NAT router from the PPC and the rest of the system. This enables the ESS channel to be modularized – i.e. every ESS channel internally uses the same set of static IP addresses on all network-connected devices. The NAT router on each ESS channel would have a distinct WAN-side IP address that identifies the channel, but would look identical on the LAN-side.

The channel NAT router would use port-forwarding of ports other than port 502 (Modbus TCP) to enable the PPC to communicate with channel devices. That is, it will have a port-forward setup for each Modbus TCP device.

There is no one-size-fits-all solution for network architecture; network architecture needs must be examined on a project-by-project basis. Nevertheless, there are essentially two styles of network topology that should be considered for any given project:

- Non-redundant network topology
- PRP/HSR redundant network topology

A non-redundant network topology may be preferable for smaller installations to minimize installation cost and complexity of long-term support. This topology is simple to implement and is relatively low cost, but there are single-point failures which can force the plant to go offline.

For larger installations, the system design may require redundancy for high availability in case of device failure. That is, there may be a need for some or all of the network connections to be redundant, such that there is no single-point device failure which can cause the entire plant to go offline.

A flat redundant network topology makes use of sophisticated hi-end routers at the central control location (e.g. co-located with the PPC), with dual fiber links directly from the routers to each of the channels. The high-end routers would have reachability rules, such that IP packets can be re-routed to reach the correct destination if the destination device is unreachable using the primary route.

PRP/HSR are protocols for network redundancy with very fast recovery to failure of network devices. The PPC Other redundancy methods exist as well. For example, each layer would be a self-healing fiber ring which could re-route IP packets at that layer if a device in the primary path fails.

NOTE: The selected method of network redundancy will affect the PPC hardware selection and consequently project cost.

Figure 9 Illustrates a redundant configuration where only the Site Firewall and RedBox ("PRP/HSR redundancy" box) would be single-point failures.

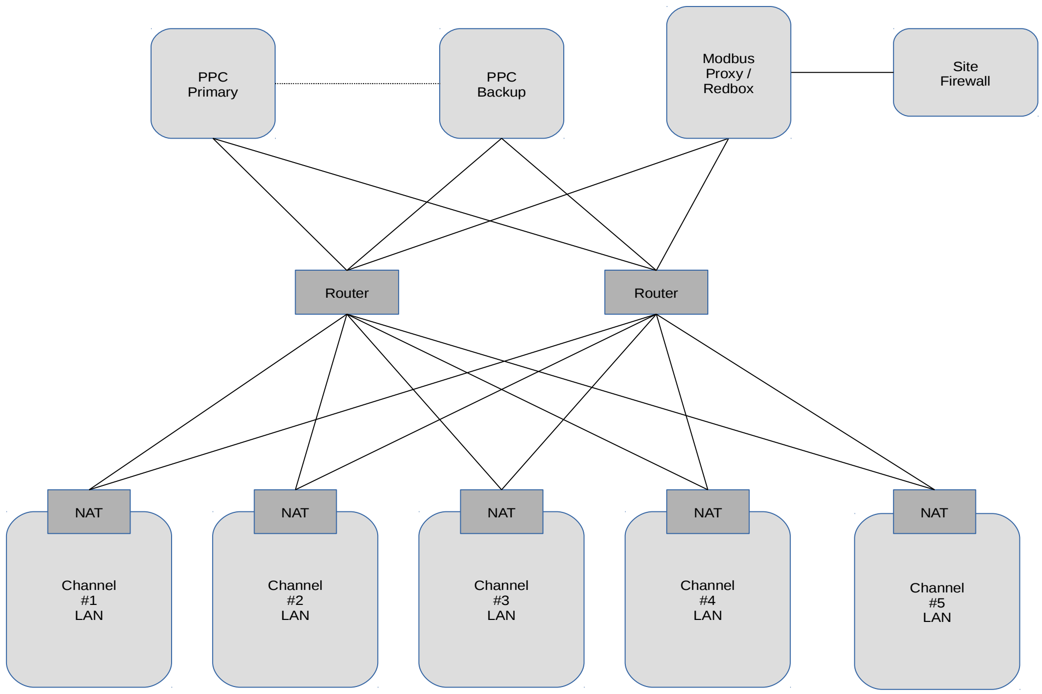

Figure 10: Example of PRP/HSR redundant network topology

7.2. On-Site Installation Support

If required, IDI personnel can travel to the site and assist with on-site installation. After the customer gains some familiarity with the PPC system, this is not normally required.

7.3. NERC CIP

The North American Electric Reliability Corporation (NERC) Critical Infrastructure Protection (CIP) standards place requirements for operating the bulk electric system. The standards define a minimum set of processes and controls for transmission, distribution, and generation companies. The standards are primarily about processes and controls, but they have implications for the technical infrastructure.

While the PPC software is designed to work in a NERC CIP compliant installation, the PPC itself cannot make the system compliant. Indeed, compliance is about how the company operates the system as much as it is about what the technical specifications of the system are.

IDI offers professional services to assist the integrator in ensuring the system meets the technical requirements for compliance, and to assist the eventual owner in setting up their infrastructure and processes to operate the system in compliance over its lifetime.

7.4. Modeling and Simulation

IDI offers professional services for modeling and simulation of complete ESS systems integrated into the grid. Such simulations should be used to predict performance of the integrated system under scenarios such as loss of generation, frequency events, and intermittency from a solar PV or wind power plant.

If a custom control strategy is to be developed for a given installation, then modeling and simulation is an essential part of the development process that would be proposed. However, it can be valuable even if the plan is to use a built-in or preexisting custom control strategy.

Modeling and simulation can be performed to obtain an in-depth analysis, or it can be performed to provide an overview of performance under some basic scenarios. Similarly, the analysis can look at sub-cycle response over 1-2 second transient events, or at aggregated system response over day-long periods of time. The purpose of any given modeling and analysis effort – i.e. the questions that need to be answered – must be clearly defined before the work can be quoted or performed.

IDI offers MATLAB / Simulink modeling for all control algorithm development efforts, and can extend our analysis offerings to use power-systems modeling tools such as PSS/E, PSLF, etc. where needed for a particular customer project.

7.5. Controller-in-the-Loop Test Environment

IDI has developed a “controller-in-the-loop” simulation environment for testing PPC features and interfaces. This test environment enables testing of all device interfaces and functions before integration testing with delivery partner equipment, and before delivery to the field.

Additionally, the controller-in-the-loop test environment includes a simple but flexible simulation of grid dynamics that makes it possible to make realistic response-time and algorithm performance assessments and optimization. For example, IDI uses the test environment to accurately estimate response time with a given PCS and instrumentation configuring for high-speed closed loop control strategies, such as micro-grid applications requiring very fast response to frequency or voltage transients. The PPC is normally the fastest component in the system, so the overall system must be analyzed to understand system-level performance.

Taken together, these capabilities enable us to maintain consistently high quality, with predictable performance, and with a very low rated of fielded defects.

7.6. Changes to Built-In Features

If a customer requests an change to a built-in feature which, in IDI’s judgment, is of sufficiently general merit to warrant incorporation into future versions of our base offering, then IDI will cost-share the change, charging half the normal professional services rate for making the change.

If, in IDI’s judgment, the requested change is not sufficiently general to warrant incorporation into the base offering, then IDI may offer to implement a custom feature to achieve the customer’s objectives, which would be performed entirely at the standard professional services rate.

Similarly, if a feature on IDI's roadmap is planned for future implementation, but a customer needs the feature for a current project, IDI may offer to implement the feature earlier than otherwise planned. IDI may ask the customer to cost-share the early implementation of the feature.

8. Pricing Framework

When a new project opportunity occurs, IDI will evaluate the need and produce a quote. Each quote will be organized as shown below. See a separate spreadsheet for current pricing rates.

Line Item	Price
PPC core	Fixed price
PPC extended features	Fixed price based on features selected, plus MW-rating multiplier.
Pre-existing custom features previously developed for the customer	Fixed price per pre-existing feature, to cover regression testing on the bench.
Development of new custom features	Hourly rate for professional service; estimated based on SOW.
Professional services	Hourly rate for professional service; estimated based on SOW.

As an example, suppose a new basic single-channel system is to be quoted, and suppose the required PCS interface and BMS interface features have already been developed from prior projects. If the project is small enough that no custom development is required, and no professional services are required, and the extended features are not required, then the price could be simply the PPC core. This will make small demonstration projects very cost-effective.