

 DESIGN PRACTICES	<i>ELECTRIC POWER FACILITIES</i> INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	Section XXX-F	Page 1 of 44
		December, 2003	

Changes shown by ↕

CONTENTS

SECTION	PAGE
SCOPE	3
REFERENCES	3
INTRODUCTION	3
DEFINITIONS	3
LOAD CLASSIFICATION.....	5
Load Characteristics.....	5
Planning Considerations	6
Hierarchy of Supply and Selection	6
D-C Instruments	8
A-C Instruments	8
General Considerations for Distribution and Utilization of An IPS	8
Sizing a Power Supply System.....	9
SOURCES OF POWER.....	9
Control Center Power Supply	9
Normal Power Source Considerations	9
Alternate Power Source Options	10
Branch Circuit Protection.....	10
TYPES OF INSTRUMENT POWER SUPPLY SYSTEMS.....	11
Instrument Power Supply (IPS) Functional Description.....	11
Types of IPS Systems	12
Comparison of Static and Rotary Systems	14
Comparison of Industrial and Commercial Grade Instrument Power Supply Systems	15
EQUIPMENT	15
Static Inverter Designs	15
Voltage Stabilizers.....	16
Batteries	17
Battery Chargers And Rectifiers	19
Standby Generators	20
Transfer Switches.....	20
Essential Services Loads	21
APPENDIX A BEST PRACTICE FOR BATTERIES, BATTERY CHARGERS, AND INSTRUMENT POWER SUPPLIES	40
APPENDIX B GENERIC MAINTENANCE STRATEGY FOR BATTERIES	44

Section	Page	<i>ELECTRIC POWER FACILITES</i> INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	 DESIGN PRACTICES
XXX-F	2 of 44		
December, 2003			

FIGURES

Figure 1 Static Inverter Instrument Power Supply (IPS) System22

Figure 2 IPS Modes Of Operation23

Figure 3 On-Line IPS System.....24

Figure 4 Off-Line IPS System.....25

Figure 5 Rotary IPS Systems26

Figure 6 Ferroresonant Inverter.....27

Figure 7 PWM Inverters28

Figure 8 Redundant IPS System Configurations29

Figure 9 Typical Overload Limits30

Figure 10 Power Distribution Feeder Designs31

Figure 11 Load Sharing Redundant UPS - Typical.....32

Figure 12 Distributed Redundant UPS - Typical.....33

Figure 13 Automatic Transfer System Essential Services Switchgear34

Figure 14 Automatic Transfer and Protection Circuits for Essential Services Switchgear35

Figure 15 Symbol and Functions Legend.....39

Revision Memo

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<div></div> <div>DESIGN PRACTICES</div>	<div><i>ELECTRIC POWER FACILITIES</i></div> <div>INSTRUMENT AND ESSENTIAL SERVICES</div> <div>POWER SUPPLIES</div>	Section	Page
		XXX-F	3 of 44
		December, 2003	

SCOPE

This section provides guidelines for the design, selection, installation, application, and testing of systems and equipment supplying power to essential instrumentation and other essential services normally used in ExxonMobil plants.

This section covers power supplies for instrumentation, controls, and essential services that are required during general power outages. Also covered are power supplies for non-essential services whose loss may be tolerated during general power outages. The electric power distribution system, from the main purchased power substation or in-plant generator switchgear to the plant unit substations, is covered in section XXX-C.

REFERENCES

IEEE Std 446 - IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (IEEE Orange Book)

IEEE C62.41 - Recommended Practice on Surge Voltage in Low-Voltage A-C Power Circuits

NEMA PE 1 - Uninterruptible Power Systems

NFPA 110 - Standard for Emergency and Standby Power Systems

NFPA 111 - Standard on Stored Energy Emergency and Standby Power Systems

GLOBAL PRACTICES

GP 15 -7-1 Electric Power Branch Circuit Design for Instrumentation

GP 16-8-1 Instrument and Essential Services Power Supplies

GP 16-12-1 Switchgear, Control Centers and Bus Duct

DESIGN PRACTICES

[DP XXX-C](#) Power Distribution

INTRODUCTION

Refineries and chemical plants are designed to accommodate a total power outage. Safety critical systems, such as emergency shutdown and emergency depressurizing systems, are provided to allow a safe shutdown of the various units when all electric power is lost. Even though the electric power supply is not a safety critical system, there are instrumentation, controls, and essential services whose loss cannot be tolerated during general power outages. These loads are needed to enable a controlled unit shutdown in the event of a power outage and are thus energized from power supplies that are equipped with a normal and an independent standby source of electrical energy. Upon failure or outage of the normal source, the power supply is automatically transferred to the alternate source. The following sections provide design, selection, installation, application, and testing guidelines of power supplies for essential instrumentation, control and protective systems, and other essential services.

DEFINITIONS

Absorbed electrolyte cell

A valve-regulated lead-acid (VRLA) cell whose electrolyte has been immobilized in an absorbent separator (normally glass or polymeric fiber) and is sealed, with the exception of a valve that opens to the atmosphere when the internal gas pressure in the cell exceeds atmospheric pressure by a pre-selected amount.

Battery

Two or more cells electrically connected for producing electricity.

Charger/Rectifier

A charger is a device that converts a-c power into d-c power that is compatible with a battery's voltage and current characteristics, i.e., charge, float, equalization, etc. A rectifier is a device that converts a-c power into d-c power to supply the input power to d-c loads or an inverter, but not to a battery.

Section	Page	ELECTRIC POWER FACILITIES INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	 DESIGN PRACTICES
XXX-F	4 of 44		
December, 2003			

Critical and independent unit

A unit, or group of units, that can operate without the other plant units and represent or are needed for 20% or more of plant throughput.

Critical loads

Essential instrumentation, control and protective systems, and other essential services that are required during general power outages and whose loss cannot be tolerated during infrequent maintenance and repair of their power supply.

Equalizing charge

An extended charge to a measured end point that is given to a storage battery to insure the complete restoration of the active materials in all plates of a cell.

Essential instrumentation and control and protective systems

- Transmitters, controllers, recorders, indicators
- Computers, digital control systems, and related equipment
- Stream analyzers
- Startup, sequence, shutdown, and emergency trip systems
- Valve actuators
- Annunciators, monitors, alarms, and telemetry
- Drives in purging, pressurizing, and air conditioning systems necessary for operation of essential instrumentation

Essential services

- Radio or other communications equipment needed during a power outage
- Control house (or room) emergency lighting
- Drives in purging, pressurizing, and air conditioning systems necessary for maintaining a non-hazardous (unclassified) building area classification
- Boiler drum gage glass lighting
- Motor operated valves in emergency service

Instrument power supply (IPS)

A system that provides continuous regulated power to a load. When a battery and an alternate power source are included, the system continues to supply the load during any periods when the normal power source is unavailable or is outside of specified limits. (This type of system is sometimes referred to as a UPS (see uninterruptible power supply definition below) even though power to the load would be interrupted for a failure of the power supply components, e.g., transfer switch, bypass switch, or output feeder/bus.)

Non-essential loads

Instrumentation, controls, and services that are not required during general power outages and whose loss can be tolerated during infrequent maintenance and repair of their power supply.

Rotary instrument power supply

A power supply that uses a rotating a-c generator to generate the usable output power. The a-c generator is driven by an a-c or d-c motor and uses its rotating inertia or a flywheel to ride through momentary/brief power outages.

Solid-state instrument power supply

A power supply comprised of an inverter, charger, and static switch made up of semiconductors and other static components such as resistors, capacitors, etc.

Tolerable transfer and outage times

The longest supply interruption that will not have a significant effect on process or equipment operation.

Uninterruptible power supply (UPS)

A system designed with sufficient redundancy so that there are no common failure points. In the event of a component failure, the remaining hardware continues to supply the load without being affected by the failure. A UPS system can accommodate a failure in the power supply unit itself, as well as loss of the normal power source. A UPS has a higher availability of supply than an IPS.

Vented cell

A cell design that is characterized by an excess of free electrolyte, and in which the products of electrolysis and evaporation can freely exit the cell through a vent. (Also referred to as flooded cell, wet cell, or Plante'.)

 DESIGN PRACTICES	ELECTRIC POWER FACILITIES INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	Section XXX-F	Page 5 of 44
		December, 2003	

LOAD CLASSIFICATION

Load Characteristics

The first and most important step in designing a power supply is to know and understand the load's power requirements and characteristics. The tolerable power outage time is a key criteria for classifying a-c loads. The following table shows four classifications for a-c essential instrumentation and other essential service loads based on the tolerable time of transfer between normal and standby supplies.

TOLERABLE TRANSFER TIME (seconds)	CLASS
0.005 (approx. 1/4 cycle) or less	I
over 0.005 to 0.2 (10 - 12 cycles)	II
Over 0.2 - 10 ⁽¹⁾	III
Transfer to Standby Not Required	Non-essential services

Note: (1) Normal transfer time is approximately 10 seconds for a diesel driven standby generator and may be 30 seconds or more if repeated start attempts are required.

D-C instrument loads are classified based on battery (capacity) back-up time requirements, voltage and ripple tolerance, diode supply requirements, etc. Tolerable outage time is normally less than 10 msec.

The load will generally determine the size and type of power supply system selected. A power supply is not a stiff source like the utility and its ability to absorb harmonics, operate in overload, and provide fault current for protective devices is limited. In order to maintain stable and reliable operation at essential instrumentation and controls, such as DCS equipment or other process control and computer systems, a high quality power source must be provided. A power supply should be selected only after carefully examining the quality of the power sources available.

A review of the critical load's acceptable power limits must be made for each piece of equipment connected to the power supply system. Since limits will vary for each type of equipment and between manufacturers of the same equipment. The following load information is required:

- normal operating voltage range (V_{max} - V_{min})
- single phase or three phase power
- allowable voltage dips and surges (%) and duration (ride through)
- allowable frequency range (Hz)
- maximum allowable power outage duration (transfer time allowed) (msec)
- maximum power consumption (VA)
- peak inrush current and duration (A)
- crest factor
- maximum allowable total harmonic distortion (%)
- maximum allowable harmonic distortion at any single frequency (%)

The operating voltage range and the voltage surges that the load can tolerate will dictate the amount of voltage regulation needed. The frequency range that the load needs will determine what frequency regulation is needed. The maximum allowable power outage duration will define the holdup time capability of the load and set the maximum allowable transfer time. DCS's, computers, PLC's, and other equipment are non-linear loads and generate harmonic currents (crest factor) which affect the power supply design and operation.

Selecting the proper power supply system for an application involves a review of a number of power system conditions that could impact the ability of a power supply to provide quality power to the load. Six conditions should be considered for the evaluation and selection of a power supply system.

Section	Page	<div>ELECTRIC POWER FACILITIES</div> <div>INSTRUMENT AND ESSENTIAL SERVICES</div> <div>POWER SUPPLIES</div>	<div><div>ExxonMobil</div><div>DESIGN PRACTICES</div></div>
XXX-F	6 of 44		
December, 2003			

1. Lightning and surge protection - Lightning protection is absolutely essential when the power distribution system consists of overhead power lines or points of entry for lightning strikes. Most power supply units provide surge protection for low energy level dissipation and cannot handle the high energy available in lightning surges.
2. Noise isolation - Common mode noise rejection and a separately derived grounded neutral are essential to ensure a clean noise-free neutral reference so is that erroneous operation of computer and sensitive control logic circuits is avoided.
3. Voltage and frequency regulation - Voltage and frequency deviation must be maintained within the allowable operating range of the connected equipment. Predictable equipment operation outside the manufacturer's allowable range is not guaranteed.
4. Continuous power - Today most critical loads connected to power supply systems have limited loss of power ride-through capability. Typical process control equipment power supplies have allowable power failure time limits of one-half to one cycle. Power outages to the power supplies that exceed this time limitation will usually result in a severe process disturbance or shutdown.
5. Output power quality - The output voltage sine-wave of the power supply system must meet the allowable voltage range and quality. The wave form will normally be required to be sinusoidal and have a maximum crest factor of 1.41 for the entire operating load range.
6. Ability to supply non-linear loads - Non-linear loads can cause voltage waveform distortion and affect performance of the power supply. The power supply system should be designed for the maximum amount of non-linear load. In some cases derating or oversizing will be required.

Planning Considerations

Design of new facilities and/or review of existing facilities for instrument power is a complex process, but can be simplified by early planning. Planning requires matching load requirements to the source and making an educated assignment of loads and distribution. A coordinated effort with the electrical design can produce economic and reliability benefits. The following factors should be considered during planning.

- What are the vendor requirements for the power supply for the loads (cabinet, console, system, or subsystem)?
- What criticality of functions exists within the load (cabinet, console, system, or subsystem)?
- Is ride through capability required (what type and duration of power transient can the load tolerate)?
- Is the function required for safe and orderly shutdown on loss of primary power?
- Is the function designed to 'fail safe' on loss of primary power?
- What level of physical protection is required to avoid inadvertent loss of power due to damage or human error?

Hierarchy of Supply and Selection

In today's control architecture, it is not always possible or desirable to identify and isolate functions within the system in terms of their inherent criticality. In general, we must treat the entire system based on the highest order of any function within the system. In some ways this complicates the planning process and in other ways it simplifies the process. The following table offers a guide to supply selection based on the recognized importance of the contained control function. Details of the sources are defined elsewhere within this Design Practice or related Global Practices.

Description of Highest Order of Control Function	Desirable Minimum Features of the Primary Power Supply	Additional Considerations
Contains an 'energized to trip' protective element associated with risk to personnel or equipment.	Highest level of reliability and availability; e.g., redundant supply from redundant sources, battery back-up, etc.	<ul style="list-style-type: none"> • See GP 15-7-02 for Protective System Power Requirements; e.g., voltage type, voltage level, and isolation. • Need to include alarm to alert when power is not available from one or more sources. • Need to include on-line maintenance and testing facilities to ensure operation on demand; e.g., load test of battery, transfer to backup, etc.

 DESIGN PRACTICES	ELECTRIC POWER FACILITIES INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	Section	Page
		XXX-F	7 of 44
		December, 2003	

Description of Highest Order of Control Function	Desirable Features of Primary Power Supply	Additional Considerations
Contains a 'de-energized to trip' protective function.	Establish continuity of power with redundant power, back-up reserve, and batteries to allow for orderly and safe shutdown during loss of primary power.	<ul style="list-style-type: none"> See GP 15-7-02 for Protective System Power Requirements; e.g., voltage type, voltage level, and isolation. Need to include alarm to alert when power is not available from one or more sources. Economic loss due to nuisance trips may justify on-line testing facilities; e.g., load test of batteries, failover, etc. May not be able to identify a single source of power for the system and all field devices associated with it due to plant topology. Impact of partial loss of multiple supplies should be assessed.
Contains principal process control.	Establish continuity of power with redundant power, back-up reserve, and batteries to allow for continued control and/or orderly and safe shutdown during loss of primary power.	<ul style="list-style-type: none"> Need to include alarm to alert when power is not available from one or more sources. Ensure that redundant devices do not contain crossed assignment of dual power feeds to ensure that a loss of one feed will not fail both control channels in a redundant pair; e.g., control module on Channel 'A' and communication port on Channel 'B'. May not be able to identify a single source of power for the system and all field devices associated with it due to plant topology. Impact of partial loss of multiple supplies should be assessed.
Contains process monitoring, information gathering, and human supervisory interface to principal control equipment.	Distribute equipment across multiple power sources to enable restoration in a reasonable time.	<ul style="list-style-type: none"> Can normally tolerate short outages (loss of view) as long as the principal control equipment and protective systems are still functioning. By assignment of reliable power to selected equipment, dual power feed and battery back up for all equipment may not be required. Operational procedures are required for this contingency.
Single loop or single function field devices; e.g., local panels, analyzer shelters, remote operator shelters, field powered transmitters, etc.	Power should be assigned dependent on the safety, environmental, and operational importance of the device.	<ul style="list-style-type: none"> If reliable power is desired, the following safeguards should be implemented. <ul style="list-style-type: none"> Develop the reliable power source (IPS) at the load, utilizing normal power as the primary source. or Connect the load to the selected reliable power through a dedicated feeder and disallow any usage other than the intended crucial function; no utility drops, fans, heaters, convenience outlets, etc. Establish coordinated protection with fuses at each end of the feeder. <p>Establish surge protection (including lightning) at the load end of the supply.</p>

Section	Page	<i>ELECTRIC POWER FACILITIES</i> INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	 DESIGN PRACTICES
XXX-F	8 of 44		
December, 2003			

D-C Instruments

The majority of control equipment in use today is microprocessor based and ultimately d-c powered, a d-c power option should thus be considered, if available. An alternative is dual power; a-c feed, d-c regulated, with battery reserve, and internal power supplies (applicable to multi-function cabinet systems).

Advantages associated with d-c include:

- Clean power that is relatively easy to produce.
- Battery back up and/or failover is easily accomplished via a diode coupled d-c bus.
- Isolation and grounding concerns can be minimized.
- Out-of-phase issues within a cabinet are eliminated.

Disadvantages associated with d-c include:

- Distribution distances may be limited.
- Coordinated circuit protection is more difficult to define and engineer.
- Not all suppliers offer a d-c option.

A-C Instruments

Most plants require that some form of reliable a-c power is available in order to manage risk during a total plant outage. Therefore, it is natural to extend this reliable a-c power to the control equipment as well.

Advantages associated with a-c include:

- Distribution distances are less restrictive.
- Circuit protection is well defined and readily available.
- Most suppliers recognize a-c as a primary power source and have designed their internal distribution accordingly.

Disadvantages of a-c include:

- Phases for dual feed and grounding among multiple supplies and multiple suppliers are more difficult to manage.
- Clean power (frequency, ripple, wave shape) must be accounted for in many suppliers specification.
- Local safety codes for a-c generation and distribution installation vary globally.

General Considerations for Distribution and Utilization of An IPS

During design and/or review, the following considerations should be included in the Power and Grounding Plan:

- Does the power feed to the control equipment require its own isolation transformer for:
 - Clean power?
 - Ground isolation?
 - Voltage regulation or surge protection?
- Care must be exercised within the cabinet to ensure that dual power feeds are truly independent in regard to phase and ground.
- Is the power source compatible with the grounding requirements within the device (power ground, safety ground, signal reference)? Ground noise can be detrimental to the performance of the equipment.
- Is the essential IPS adequately isolated to avoid initiating and propagating disturbance events such as short circuits, spikes, and faults, which could occur on other connected loads?
- Is there a clear and concise 'map' (one-line and/or composite drawing) of the IPS and distribution?
- Complete and comprehensive checkout is often rushed or overlooked during commissioning or turnaround. A thorough live test should be planned and executed against 'predictable' results to ensure no hidden surprises upon loss of one or more power sources.

 DESIGN PRACTICES	ELECTRIC POWER FACILITIES INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	Section	Page
		XXX-F	9 of 44
		December, 2003	

- It is advisable to ensure that essential power to control equipment is not mistaken for normal non-essential power. Direct hardwiring of supply or use of a unique plug and socket, readily recognized as Instrument Power, can accomplish this.

Sizing a Power Supply System

The load characteristics and the capability of the power supply to handle those characteristics determine the minimum power supply capacity. Output capacity of power supply systems is generally based on linear type loads. For non-linear loads the output capacity must be determined based on the load power characteristics during steady state and inrush conditions.

A non-linear load will affect the apparent load requirements by 10 to 40 percent. The crest factor and harmonic content of the load will determine the differential between the reported load and the capacity of the power supply. Under steady state conditions, the power requirement is typically calculated by determining the consumption of the connected load plus future loads and multiplying by a 1.2 safety factor. The power supply should be designed to handle an expected peak current of 2.5 to 3.0 times the calculated RMS value without going into current limit or transferring to bypass power. The manufacturer will state what crest factor and harmonic content the power supply can handle at the rated volt-amperes. The particular power supply system may have to be derated to accommodate the non-linear load.

When power is initially applied to the load, a high inrush current up to several times normal and lasting several cycles will occur. This can also happen following a fault or break before make transfer. A careful review of the power supply system and the bypass power system should be conducted to determine if the inrush current can be properly supplied without affecting the operation of the connected load.

Starting and transient loads should also be considered. Motors and other similar loads have a high starting load demand. Power supplies can only handle limited overloads, for short periods of time (see [Figure 9](#)). At a specific current level the voltage falls off rapidly. If the power supply does not have the required capacity, the load will transfer to bypass. The decision should be made whether this transfer is acceptable. If the power supply must transfer to bypass to start the load due to high transient current, the load will not be able to be started if the bypass is not available. The use of a static switch transfer to the alternate power source to accommodate motor starting is normally not acceptable for critical loads.

A possible concern with oversizing the power supply is decreased efficiency. Most inverters operate at their most efficient point near full load. Pulse width modulation (PWM) inverters in general have a higher efficiency than ferroresonant inverters at reduced load. The main criteria in specifying and designing an IPS system should be reliability not efficiency since the efficiency difference between the most efficient or least efficient IPS system is negligible when compared to the plant total power consumption.

SOURCES OF POWER

Control Center Power Supply

The recommended power source configurations for control center power supplies are shown in Figure 1 of GP 16-8-1. In general, power supplies for essential loads should be supplied via two feeders, with each feeder from a separate and independent power source. The configuration used for a specific application will depend on whether it is a grass roots facility or a revamp/expansion of an existing facility. It will also depend on the type of substation, i.e., radial vs. secondary selective and whether or not there is a standby generator.

Normal Power Source Considerations

The power distribution system feeding power supplies for essential loads should be carefully designed and sized for both the normal and abnormal power requirements. It is preferred that the power distribution system be designed with independent feeders for the normal and alternate power sources.

The normal source power feeder should be sized for the maximum inverter power requirements plus battery recharging. As a rule of thumb, the normal source power feeder's minimum sizing criteria should be based on the inverter power rating (P_i) divided by the power supply efficiency (approximately 0.8) times battery charging factor (1.25 - 1.50). The normal source feeder capacity can be up to 1.5 to 2.0 times the inverter rating. The alternate source power feeder for a dual feeder supply should be sized for only the inverter output power rating as this is the maximum expected load.

For a dual feeder supply design as shown in [Figures 10\(a\) & 10\(b\)](#), each feeder should be sized for its maximum load. The inverter output rating is 100 amperes. Under normal conditions without battery recharging, 130 amperes will flow to the rectifier. After battery discharging and during the recharging cycle, the rectifier input requirement will be 180 amperes.

Section	Page	<i>ELECTRIC POWER FACILITES</i> INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	 DESIGN PRACTICES
XXX-F	10 of 44		
December, 2003			

value is equivalent to 1.8 times the inverter rating. During load operation on the alternate source, 100 amperes will be supplied to the load. As this example shows, the primary source feeder should be sized for 180 amperes and the alternate source feeder should be sized for 100 amperes.

For a single feeder supply design as shown in [Figure 10\(c\)](#), both the normal and alternate power sources are supplied from the same feeder. The feeder should be sized for both the maximum normal input power demand and the alternate power requirement. The maximum input to the rectifier will always be during battery recharging, regardless of the amount of inverter load. In our example, the maximum current during the battery recharging cycle is 180 amperes even with no load connected on the inverter. During load operation on the alternate source and simultaneous battery recharging, the maximum current requirement will be 280 amperes (180A + 100A). Therefore, the single feeder supply should be designed for 280 amperes. As an alternative to providing the larger feeder, the power supply system could be supplied with a rectifier input current limiter that would automatically reduce the a-c input current to 25 - 50 percent of nominal whenever the load is powered from the alternate source.

In an application where a standby generator is used in the primary source to extend the power supply operating time during power outages, it may be desirable to delay battery recharging when connected to the standby generator until the normal a-c power is restored. In this way the engine-generator does not have to be sized to provide the additional recharging current.

The rectifier represents a large non-linear load to the normal power supply system and can induce a significant amount of voltage distortion on the power line. The resultant voltage distortion can adversely affect other loads connected to the incoming power system. It is also important to minimize the effect of voltage distortion caused by non-linear loads. Excessive voltage distortion or voltage notching that results in abnormal zero-crossover points can cause improper operation of the engine governor and inability to carry the connected load. Rectifier operation can also cause problems of overheating of the generator rotor due to harmonics and negative sequence currents. The negative and positive sequence currents of the higher harmonics add together on the rotor to cause additional heating. When a rectifier is operated with a standby generator, the generator must be designed to carry the additional harmonic currents from the rectifier. Steps may be taken to reduce the harmonic currents by using 12-pulse versus 6-pulse rectifiers or by adding harmonic filters on the rectifier input. The generator could also be designed to operate with higher negative sequence currents. As a general rule of thumb, the standby generator should be sized for at least two times the total amount of connected nonlinear load to prevent potential problems.

Alternate Power Source Options

Two options that can be added to the alternate source power to improve its overall performance are isolation and voltage regulating transformers.

An isolation transformer with a Faraday shield between windings provides excellent common mode noise rejection due to the low capacitance between the primary and secondary windings. Capacitive or electrostatic coupling is the only way common mode noise voltages can be transmitted from primary to secondary. Grounding the secondary of the isolation transformer will provide a clean noise-free ground for computer operation and reference. Isolation transformers provide only limited attenuation of transverse (normal) mode transients. The isolation transformers cannot adjust its voltage output for voltage sags or surges on the input line.

The voltage regulating transformer will maintain a relatively constant output voltage with usually $\pm 20\%$ change of nominal input voltage. With a 1 to 3 second response time, mechanical type regulators are relatively slow to respond to sudden changes in supply voltage caused by motor starting or capacitor switching. Static type regulators have a faster response time of 10 to 20 cycles. Other types of voltage regulating transformers are also available using ferroresonant technology, but are generally more sensitive to load changes, i.e., power factor, frequency, etc. In selecting the static regulator, consideration should be given to its lower efficiency and higher harmonic distortion.

Branch Circuit Protection

The fault clearing capability of the power supply is another factor that should be considered during the development of the IPS system requirements. If the IPS system cannot provide sufficient fault current from the inverter to clear a branch circuit protective device, a transfer to the alternate power source will be required. If the alternate source is not available, the power supply output will be current limited by reducing the output voltage to near zero. This will result in a loss of power to the other connected loads on the power supply system for the duration that it takes the protective device to clear the fault. Depending on the size and type of power supply, the time to clear the fault may be rather long. If the fault clearing time exceeds the maximum power outage tolerance of the connected loads, the results may be unacceptable. Coordination is also required between all internal protective devices in the normal and alternate power source equipment sections and protective devices in the down-stream distribution sections.

IPS technologies can be separated into two basic categories: closed-loop regulation, such as PWM inverters, and open-loop regulation, such as ferroresonant inverters.

 DESIGN PRACTICES	ELECTRIC POWER FACILITIES INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	Section	Page
		XXX-F	11 of 44
		December, 2003	

The PWM (closed-loop) system uses electronic feedback circuits to regulate the system output. During a branch circuit fault, the closed-loop system will react immediately to limit the let-through current so that the ratings of the solid state components are not exceeded. This prevents damage to the inverter. Due to the smaller magnetic components used in the PWM inverter design, limited stored energy is available. The combination of current limiting and low stored energy requires load transfer to the alternate power source for fault current support.

The ferroresonant (open-loop) design utilizes large magnetic components in the output for voltage regulation and inherent current limiting. The energy stored within the magnetic components provides an increased level of fault current support for a longer period of time.

The limited fault support of the PWM and the not-so-limited fault support of the ferroresonant inverter designs requires a closer look at the sizing and selection of the branch circuit protective devices.

The time-current characteristics of protective devices should be checked to determine if the fault can be cleared by the branch circuit with the available fault current and within the acceptable power outage time of the critical load, usually less than one cycle. Typically, fast acting magnetic trip circuit breakers or current limiting fuses will be required for branch circuit protection. The term current limiting fuses does not necessarily mean that the fuse will limit the fault current to an acceptable value on a limited fault current capacity system. The fuses can interrupt the fault current in a very brief period of time, usually less than one-quarter cycle, and limit the peak let-through if a sufficiently large fault current is available from the power source. This situation will depend on the relative size of the fuse as compared to power supply size and type.

Another factor that should be considered is the inrush current characteristics of the loads. Most loads have step-down transformers and frequently have input filters that result in considerable surges of current upon initial energization. If the branch circuit protective device is selected based only on steady state load current and the limited fault current available, the protective device may trip due to the high inrush current. This generally occurs when extremely fast acting fuses are used and are sized too close to the steady state operating current of the load.

Increased fault current or overload capacity of the inverter, compared to the branch circuit protective device size, can also be achieved by using larger inverters or use of inverters with single phase rather than three phase outputs.

TYPES OF INSTRUMENT POWER SUPPLY SYSTEMS

Instrument Power Supply (IPS) Functional Description

A typical static inverter IPS system, shown in [Figure 1](#), provides continuous regulated, sine wave power to the connected a-c load from the inverter through manual and static bypass switches. The rectifier provides a regulated d-c supply source to both the battery and the inverter for normal operation and recharges the battery either in a float or equalize mode. The battery and inverter filter incoming transients and provide regulated voltage and frequency to the load even if the line voltage and frequency should stray outside of acceptable tolerances.

The inverter converts the incoming d-c power to a regulated a-c output power for the connected load and is normally synchronized to the alternate power source. The output frequency of the inverter should be controlled by an oscillator that can be operated as a free-running unit or as a slave for synchronized operation with the alternate power source. The inverter shall track the synchronized alternate supply. If the alternate supply frequency deviates from preset limits, the oscillator shall automatically revert to a free-running unit. When acceptable line frequency on the alternate source has returned, the inverter will resynchronize to it.

Upon failure of the incoming a-c power supply or the rectifier, the battery will supply power to the inverter without power interruption to the load. The inverter output voltage and frequency will remain constant as the battery discharges to its minimum value, typically 1.75 volts per cell for lead acid type batteries. The amount of battery capacity is determined by the time specified for the inverter to provide rated output power (voltage, current and frequency) to the critical load.

The inverter output power is supplied to the load through a static transfer switch. Provided the inverter output is in synchronism with the alternate source, the static transfer switch will automatically transfer the load to the alternate power source, without interruption, upon loss of the normal power source, when the normal power source is outside of specified limits, if there is an excessive overload, or if there is a fault upstream of the static switch. A manual make-before-break bypass switch is used to bypass the IPS system for maintenance or system repairs/replacements.

Note that if there is fault in the static transfer switch, the manual bypass switch, or the output feeder/ distribution bus, the power supply to the load will be lost. For this reason, this type of system is not an uninterruptible power supply (UPS) and it is referred to as an IPS in this Design Practice and in the GPs. Even though industry jargon and many practitioners refer to this type of system as a UPS, it should be recognized that there are failure modes that will cause a loss of power to the load.

<div>Section</div> <div>Page</div>		<div><div>ELECTRIC POWER FACILITIES</div><div>INSTRUMENT AND ESSENTIAL SERVICES</div><div>POWER SUPPLIES</div></div> <div><div><div>ExxonMobil</div></div><div>DESIGN PRACTICES</div></div>
<div>XXX-F</div>	<div>12 of 44</div>	
<div>December, 2003</div>		

Only critical loads should not be supplied from the IPS. Supplying non-critical a-c loads from the IPS a-c distribution bus, tapping the battery for partial voltage d-c loads, or supplying non-critical d-c loads by tapping the battery feeder cable, even though this may be the most convenient power source, should be avoided.

There are four modes of operation for a static IPS system, as shown in [Figure 2](#). In the "normal operation" mode, [Figure 2\(a\)](#), the rectifier/charger provides d-c current to the inverter while maintaining the batteries at full charge. The "emergency" mode, [Figure 2\(b\)](#), provides d-c power from the battery for the inverter upon failure of the normal power source or rectifier. During battery discharge the inverter output voltage remains stable. The amount of time the inverter can supply the load depends on the battery capacity and the size of the load. The "recovery or recharging" mode, [Figure 2\(c\)](#), begins upon restoration of the normal power source. During this period, the input to the rectifier increases to the current limit setting, to provide d-c current to the inverter and d-c current to recharge the battery. As the battery charger reaches normal level, the static IPS system returns to "normal operation" mode. The "bypass" mode, [Figure 2\(d\)](#), occurs when the inverter malfunctions, the load exceeds the inverter capability, or the load is intentionally transferred to the alternate power source. During this mode, the alternate power source supplies the load while the normal power source continues to provide the power for battery charging or recharging.

Types of IPS Systems

The configuration of an IPS determines the classification and use of the system. In industry, there are many names for similar configurations, causing confusion for the end user. A one-line diagram of the IPS will reduce confusion and define the configuration. Most single-module IPSs can be placed into one of four general categories: on-line, off-line, rotary, or hybrid.

On-Line IPS System

The most commonly used system is the on-line IPS shown in [Figure 3](#), which continuously supplies the load with a-c power. The normal a-c voltage source is converted to a constant d-c voltage by a battery charger/rectifier and then converted back to an a-c voltage with an inverter. The rectifier is sized large enough to supply rated power to the inverter plus additional power to fully recharge the batteries within a specified time period (GP requirement is 8 hours). On-line systems, also known as the reverse-transfer type, continually supply the total power requirements for the critical load. In the event of a power failure on the normal a-c source, the batteries instantly supply the power to the inverter without an interruption of power to the critical load. The a-c output is completely isolated from the normal source by the double conversion of the incoming power from a-c to d-c and then d-c to a-c.

Most on-line IPS systems are purchased with a fast static transfer switch downstream of the inverter to increase the availability of power to the connected load. In the event of an inverter failure, the static transfer switch will transfer to the alternate power supply in a 1/4 cycle or less. To assist the transfer, the inverter output is maintained in synchronism with the alternate power supply. For Class I loads, a make-before-break maintenance bypass switch should be provided downstream to allow normal periodic maintenance while the load is being supplied from the alternate power source. For Class II and III loads, the manual bypass switch with break-before-make operation and a transfer time of less than 100 msec should be provided.

Based on the site electrical conditions and the quality of power, the alternate power supply may require some type of power conditioning. This may consist of filters, surge suppressors, isolation transformers, or regulating transformers.

Off-Line IPS System

An off-line IPS system, as shown in [Figure 4](#), consists of the same components as the on-line IPS but provides power to the critical load directly from the normal a-c power source. The inverter system provides power to the load only when power line disturbances are sensed. Load transfer from the normal source to the inverter may take between a fraction of a cycle to several cycles depending on the type of power line disturbance and transfer switch used. Since the inverter is not normally operating, the off-line IPS is highly efficient and has low audible noise level.

The automatic transfer switch will take approximately one cycle or less to switch in optimum conditions (steady state conditions at rated voltage followed by a complete loss of voltage). The switch-over time will increase if the normal supply voltage experiences a gradual decrease. Low voltage conditions that are above the transfer setpoint often precede a complete loss of voltage, and the loss of power due to transfer after a low voltage condition could be much longer than the rated transfer time. Some loads such as switching mode power supplies require a faster transfer time to prevent shutdown when operated at reduced voltage prior to the complete loss of power. The result is that, in a reduced voltage condition prior to a complete loss of power, the off-line IPS may not transfer to the inverter in time to keep the load from shutting down.

There is another problem associated with the off-line IPS system during low a-c line voltage. If the setpoint transfer voltage is raised to initiate an earlier transfer time during low voltage conditions, the IPS will transfer to the inverter and start to discharge the battery sooner. Battery chargers for off-line IPS systems are normally sized to charge the battery in a reasonable amount of time, usually 8 hours, and are not large enough to supply the load. If the low voltage condition continues, the battery will be fully discharged and the load will lose power even though there may be an adequate voltage level to run the load on the a-c line at the reduced voltage condition.

 DESIGN PRACTICES	ELECTRIC POWER FACILITIES INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	Section	Page
		XXX-F	13 of 44
		December, 2003	

The off-line IPS inverter is designed for limited use, not sized for continuous duty, and will normally be operating within its systems infant mortality life. Due to the lack of complete line conditioning and voltage regulation, the off-line unit is small and inexpensive. A limited advantage is that the load is directly fed from the a-c line and therefore it operates more efficiently. The higher efficiency occurs since there is no conversion of power and resulting unit power losses.

Optional features available on the off-line IPS are automatic synchronizing, static transfer switch, and manual bypass. These additions may solve problems with low a-c line voltage transfer conditions but will increase the cost of the unit. In general, the off-line IPS systems are used in non-critical functions such as in office installations where its loss would only affect single PC user or for loads such as emergency lighting which require backup but can tolerate momentary loss of power and loads which have broader power supply tolerance.

Rotary IPS System

The rotary IPS system uses a rotating a-c generator to generate usable output power. They use their rotating inertia to ride-through input voltage sags or total loss of the normal a-c source for periods up to 1/2 second (500 msec). When a flywheel is added, the ride-through time can be several seconds. For protection against loss of power lasting more than 1/2 second, batteries or other energy storage devices may be added. Conversion of battery power to rotating power may be accomplished by use of a d-c motor or with a solid state inverter feeding an a-c motor. There are a number of system variations that eliminate the need for batteries. One vendor uses a diesel prime mover, an induction coupling, and an a-c generator (Heemaf). Another uses a combined converter motor and a-c generator on a single stator (Unibloc). A third vendor uses a combined d-c motor and a-c generator (Monobloc).

A rotary IPS system consists of an a-c motor generator (M-G) set with a flywheel and a rectifier/battery charger, batteries, inverter static switch, and solid-state control circuitry. Generally, the M-G set and the static section (rectifier/charger, batteries, and inverter) are fed from the grid (normal source). During normal operation, the M-G set powers the loads, while the offline static section is on "standby" and charging the batteries. Upon loss of the normal source, the control circuitry disconnects the M-G set from the utility by opening the static switch and closing inverter output circuit breaker, which allows the system batteries to power the M-G set through the inverter. Mechanical energy stored in the flywheel allows the M-G to continue to deliver full load power during the transfer time.

The selection of an induction versus a synchronous motor is an important design consideration. The induction motor offers simplicity in construction and application as compared to the synchronous motor without the need of additional control circuitry for field excitation. The main advantage of the synchronous motor is the flat speed versus load response with no slip for increased load. Therefore, the generator will maintain a constant output frequency over its entire rated load range. The induction motor speed slip will increase with additional load resulting in lower output frequency to the load. Several methods can be used to minimize the slip of an induction motor, however the result is increased cost and complexity.

- Use a low slip motor design to reduce the amount of slip for a given load range.
- Use a wound-rotor induction motor to adjust field resistance and increase torque with increased load.
- Use an adjustable frequency drive with the motor to control a constant output speed over the load range.

Several different configurations of rotary IPS systems are shown in [Figure 5](#). The rotary IPS unit shown in [Figure 5a](#), is an improved application of a motor-generator set with standby battery equipment for power outage ride-through capability. The rotary IPS unit in its simplest form consists of a synchronous or induction motor directly connected to the normal power source and driving a synchronous generator. Either a d-c motor or static inverter connected to the normal input drive motor is used to drive the synchronous generator in case of a power failure on the normal power source. The battery charger is connected to the normal a-c power supply for battery charging. The rotary IPS can also be provided with static and manual bypass switches for increased power supply security.

Another type ([Figure 5b](#)) uses a static inverter to drive the a-c motor and eliminates the need for the d-c motor. Other types ([Figure 5c](#)) are used to override very short power outages on the normal power source while the synchronous motor is being transferred to another power source. In this case, a flywheel is used to provide the energy necessary to drive the synchronous generator while the primary source is being switched.

The following section describes the Hitec (formerly known as Holec) system that is installed at a number of ExxonMobil locations.

Heemaf Rotary System

The Hitec system (Heemaf) consists of a diesel prime mover, an induction coupling, and a synchronous three-phase a-c machine. The induction coupling incorporates two rotary parts; the outer is provided with an a-c winding and a d-c winding. The inner part of the induction coupling and the diesel generator are separated from each other by a free-wheeling coupling. The flexible coupling links the outer part to the self-regulating compounded three-phase a-c machine, which is electrically connected via a choke coil to the normal power supply and the load.

Section	Page	<i>ELECTRIC POWER FACILITIES</i> INSTRUMENT AND ESSENTIAL SERVICES POWER SUPPLIES	 DESIGN PRACTICES
XXX-F	14 of 44		
December, 2003			

At normal operation, electric power is supplied to the load from the grid via a choke coil without being converted. The three-phase a-c machine, also supplied from the grid, drives, as a synchronous motor, the outer part of the induction coupling (1500 rpm on 50 Hz systems and 1800 rpm on 60 Hz systems). Since three-phase current excites the four-pole a-c winding of the rotating outer part, the inner part rotates at a speed 1500 rpm relative to the outer part (in the absolute sense at 3000 rpm). The free-wheeling coupling separates the inner part of the induction coupling from the diesel engine. During grid operation, the diesel engine remains off and the three-phase a-c machine acts as a stabilizer for the voltage supplied to the load and as a reactive current compensator for the grid current.

In the event of a disturbance or loss of the mains supply, the mains breaker (contactor) and the three-phase a-c supply circuit of the induction coupling are switched off. At the same time, the d-c winding of the induction coupling is excited, via a frequency measuring and control circuit, with the result that the inner part of the induction coupling is decelerated and thus starts to act as a kinetic energy source. The outer part of the induction coupling starts to drive the three-phase a-c machine which, as a result, changes over from motor operation to generator operation. During deceleration of the inner part of the induction coupling, the diesel engine starts and accelerates. It typically takes less than 1.5 seconds to go from standstill to 1600 rpm.

As soon as the diesel engine speed equals that of the inner part of the induction coupling (about 1600 rpm), the free-wheeling coupling engages and connects the diesel engine to the power supply circuit. At that moment, the diesel engine takes over the function of emergency-energy source from the inner part of the induction coupling. The frequency regulator controls the torque transmission between the diesel engine and the three-phase a-c machine in such a way that the power-output frequency remains constant, irrespective of any variation of the diesel engine.

When the mains power supply is restored, the gen-set and the mains are automatically synchronized. The three-phase a-c machine changes over from generator operation to motor operation, the free-wheel coupling disengages, and the inner part of the induction coupling is accelerated to the initial speed (3000 rpm). After about 3 minutes, the diesel engine is shut down.

Comparison of Static and Rotary Systems

A major advantage of the rotary IPS unit is total electrical isolation from the incoming electrical power. The mechanical separation between the motor and the generator on the rotor shaft of the rotary IPS provides total electrical isolation between the input power source and the power output. Another advantage of the rotary IPS is that the synchronous generator has low impedance unlike a static IPS, which usually has high impedance. This allows less distortion in the output waveform when supplying non-linear loads and improved fault current support to obtain better coordination of protective devices. Rotary IPS systems lend themselves toward systems of multiple sets and are often installed with redundant machines. These systems are usually designed so that additional rotary units may be added as load increases.

The evaluation of these systems will focus on four points; power quality, reliability, cost, and application considerations. The following comparison is based on typical systems and uses generalized equipment performance data. For a specific application actual equipment data should be used.

The rotary system is somewhat superior in terms of power quality. The total harmonic distortion (THD) of a typical rotary system is about 2% lower than that of a typical static system, while single static distortion (STD) is about 1% lower for a rotary system. The voltage regulating capabilities of a rotary unit are better under steady-state conditions, while under dynamic conditions the static unit has better voltage regulation. The static system provides good electrical noise isolation, whereas the inherent characteristics of an M-G set provide complete isolation of the motor's input from the generators output.

The rotary system has a theoretical MTBF of about 160,000 hours (20 years), while the static unit has a theoretical MTBF of about 100,000 hours (12 years). These are average values for typical systems and the actual MTBF values for specific systems should be compared for a particular application. In a rotary system, the bearings are the most likely component to fail and regular maintenance is required to achieve the above MTBF value.

The rotary system cost is about 25-40% higher than for a comparable static system.

The static unit generally produces more audible noise than does the rotary unit, except where the rotary unit includes a diesel prime mover. The rotary unit produces more heat and requires more space (when batteries are included) than its static counterpart. Maintenance for the rotary unit is a bit higher than for the static unit.

Despite their better power quality and higher reliability, rotary units are difficult to justify because of their significantly higher cost. Rotary units are generally not competitive in small power ratings or where multiple units are required. They are more competitive for single high power rated systems, but their higher cost is still a deterrent. The static unit is the preferred type at most ExxonMobil plants and in industry in general. There are, however, a few plants that prefer rotary units. They have had good operating experience with the rotary units and prefer them because they eliminate the need for batteries.

Hybrid IPS Systems

The hybrid category of IPS systems represents combined technologies from the on-line, off-line and rotary designs in an attempt to package the features that may be better suited for a particular application. Standard on-line IPS systems