ENERGY MANAGEMENT SYSTEM FOR THE NEW JAMNAGAR REFINERY IN INDIA

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***Abstract—**Bechtel recently executed one of the world's largest refinery projects—the new Jamnagar refinery in India for Reliance Industries Limited. This major new refinery is located adjacent to the old refinery completed by Bechtel in 1999. The new refinery's captive 800 MW power generation and electrical distribution system operates in parallel with the old refinery's captive 450 MW system. Grid connections are at 132 kV. The new refinery's electrical network comprises a 220 kV switchyard, two 33 kV main receiving substations, and nearly 40 process substations. Power is distributed at 33 kV from the main substations to the process substations, which step it down to 11 kV, 6.6 kV, and 415 V for distribution to refinery loads.*

To monitor and control this new large, complex electrical network, an ABB energy management system (EMS) was designed and installed. The specifications and functionalities of this EMS evolved out of a continuous process of Bechtel's detailed interaction with Reliance's project and operations teams. The resulting key design requirements were steady-state and dynamic performance commensurate with power system requirements, incorporation of the latest hardware and software technologies, redundancy, reliability of operation, seamless interface with the original refinery's EMS, and provision for expansion to match future network growth.

This paper discusses the development of the new refinery's EMS, including the challenges faced during its design, engineering, and execution and some of the innovative measures involved in resolving them.

***Keywords—**electrical distribution management system (EDMS), energy management system (EMS), Jamnagar, load management system (LMS), load shedding, substation automation*

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INTRODUCTION

The new Jamnagar refinery is among the largest projects executed by Bechtel. Located adjacent to Reliance Industries Limited's old refinery near Gujarat, India, the new facility increased the total refining capacity to over 1,200,000 barrels per stream day (bpsd) upon its full commissioning in 2010, making the combined refinery complex the world's largest.

The new refinery's power generation and distribution system is quite complex. The 800 MW captive power plant (CPP) and electrical network operate in parallel with the old refinery's 450 MW CPP and network. Grid connections are at 132 kV. The new refinery's electrical network comprises a 220 kV switchyard, two 33 kV main receiving substations, and nearly 40 process substations. Power is distributed at 33 kV from the main substations to the process substations, which step it down to 11 kV, 6.6 kV, and 415 V for distribution to refinery loads.

To monitor and control this new large, complex electrical network, an ABB energy management system (EMS) was designed and installed. The main features of the new refinery's EMS are:

- Electrical distribution management system (EDMS) to acquire relevant data and to control and monitor the electrical generation and distribution system
- Load management system (LMS) to carry out load shedding across both refinery networks
- Generation control (generator active and reactive power control)
- Tie-line control (inter-refinery tie-line active and reactive power control)
- Information storage and retrieval (IS&R) system
- Interfaces with other control and monitoring systems, such as the switchyard automation system (SAS) that controls and monitors the 220 kV/33 kV systems
- Interface with third-party systems, e.g., a large-screen display in the central control room (CCR) and Web interface

ABBREVIATIONS, ACRONYMS, AND TERMS

AVR	automatic voltage regulator
bpsd	barrels per stream day
CB	circuit breaker
CCR	central control room
CPP	captive power plant
DCS	distributed control system
DO	digital output
DRS	disturbance recording system
EDMS	electrical distribution management system
EMS	energy management system
GIS	gas-insulated switchgear
GPS	global positioning system
GTG	gas turbine generator
HMI	human-machine interface
I/O	input/output
ICT	interconnecting transformer
IEC	International Electrotechnical Commission
IED	intelligent electronic device
IS&R	information storage and retrieval
LAN	local area network
LMS	load management system
LPG	liquefied petroleum gas
LV	low voltage
MIS	management information system
MLS	main load-shedding system
MRS	main receiving station
MSA	modular smart array
MV	medium voltage
OPC	industry standard that defines methods for exchanging real-time automation data between PC-based clients using Microsoft® operating systems
OS	operator station
PC	personal computer
PDS	program development and testing system
RST	refinery service transformer
RTU	remote terminal unit
SAS	switchyard automation system
SNTP	simple network time protocol
SOE	sequence of events
STG	steam turbine generator
TPS	thermal power station
UFLS	under-frequency load-shedding system
VIP	virtual Internet protocol

The new refinery's EMS requirements were steady-state and dynamic performance commensurate with power system requirements, latest technologies, redundancy, reliability, seamless interface, and provision for expansion.

The key EMS design requirements were steady-state and dynamic performance commensurate with power system requirements, incorporation of the latest hardware and software technologies, redundancy, reliability of operation, seamless interface with the old refinery's EMS, and provision for expansion to match future network growth.

The new refinery's EMS is one of the largest electrical network monitoring systems supplied by ABB. This paper discusses its development, including the challenges faced during its design, engineering, and execution and some of the innovative measures involved in resolving them.

OVERVIEW OF THE JAMNAGAR REFINERY

The old Reliance Industries Limited Jamnagar oil refinery and petrochemical complex processes 650,000 bpsd of crude oil and produces liquefied petroleum gas (LPG), naphtha, gasoline, kerosene, diesel, sulfur, coke, polypropylene, and numerous aromatic products, including paraxylene, orthoxylene, and benzene, all primarily for domestic consumption. At the time Bechtel designed and constructed this project (1995 to 1999), it was the world's largest grassroots single-stream refinery. The old complex includes a CPP designed to produce 450 MW of power (backed up by a 132 kV grid supply) to meet the refinery's power demands.

The new export-oriented refinery almost doubles the overall capacity to more than 1,200,000 bpsd; adds crude distillation, associated secondary conversion facilities, and an 800 MW CPP; and modifies the old refinery to ensure the efficient operation of both refineries.

The current Jamnagar complex is now the world's largest refinery, surpassing the 940,000 bpsd Paraguana refining complex.

JAMNAGAR REFINERY POWER GENERATION AND DISTRIBUTION

Figure 1 presents a simplified diagram of the power generation and distribution systems of the new and old refineries.

New Refinery Power System

The CPP that is the new refinery's power source consists of six 125 MW, 14.5 kV gas turbine generators (GTGs), with provision for three future GTGs. The GTGs are connected to a 220 kV switchyard bus via dedicated 14.5 kV/231 kV, 161 MVA step-up transformers. Eight 220 kV/34.5 kV, 174 MVA refinery service transformers (RSTs) connected to the 220 kV switchyard feed the refinery substations through 33 kV substations in two main receiving stations (MRS 1 and MRS 2).

The current Jamnagar complex is now the world's largest refinery.

Two 11 kV, 25 MW steam turbine generators (STGs) are connected to the 33 kV switchboards

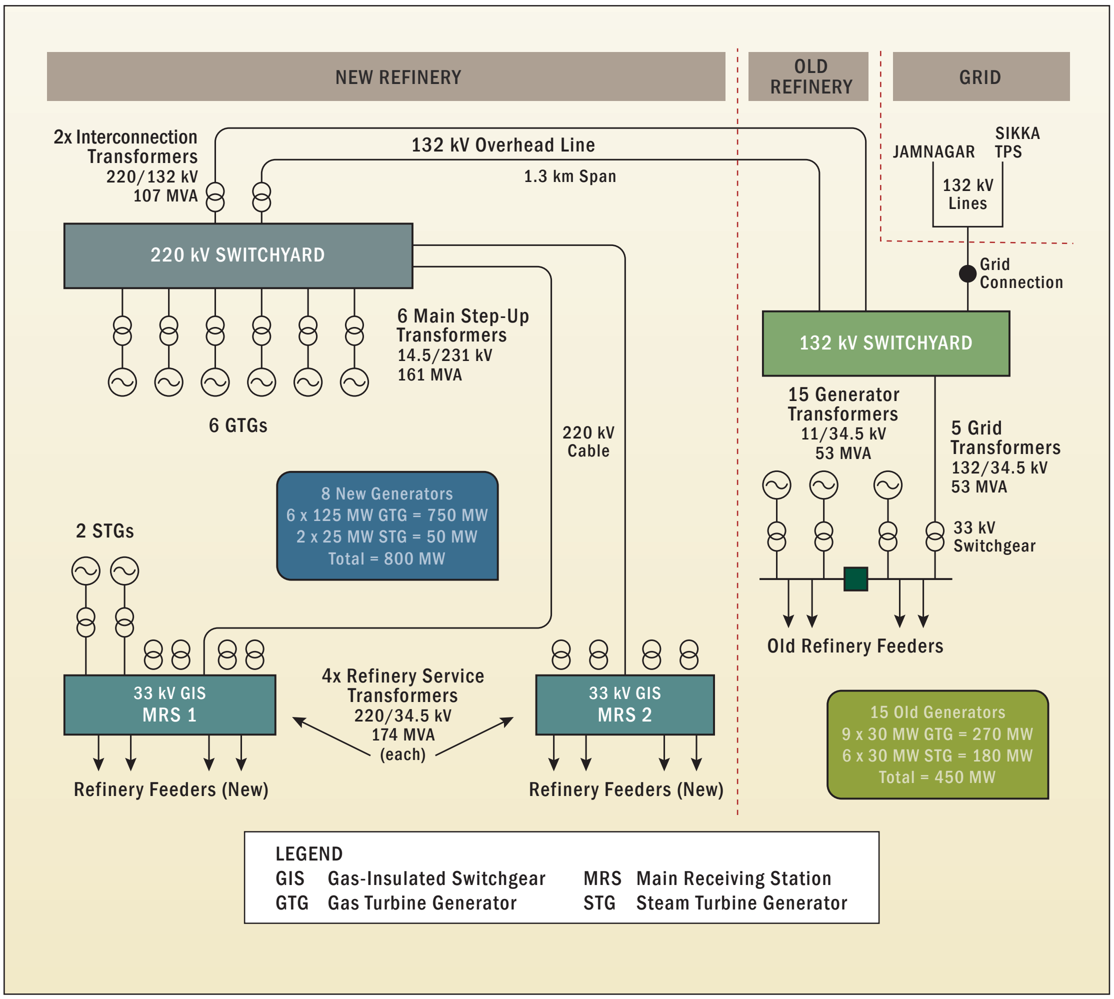

Figure 1. Power Generation and Distribution Systems of the Old and New Refineries

in MRS 1 via 11 kV/34.5 kV, 38 MVA step-up transformers.

A pair of 220 kV/132 kV, 107 MVA auto-transformers function as the interconnecting transformers (ICTs) between the new and the old electrical systems.

The available throughput from the expansion refinery's CPP is approximately 700 MW.

An EMS covers a wide array of functionalities: electrical system control and monitoring, parameter measurement and recording, report generation, contingency evaluation, emergency action execution—and more—under one umbrella.

Old Refinery Power System

The old refinery's CPP consists of nine 30 MW GTGs and six 30 MW STGs that feed five 33 kV switchboards, from which point power is further distributed to the old refinery's substations. The installed base is approximately 450 MW, and available throughput is approximately 400 MW.

EVOLUTION OF THE EMS AS A CENTRAL MONITORING AND CONTROL SYSTEM

The term *energy management system* is a broad-based term that covers a wide array of functionalities encompassing electrical system control and monitoring, key parameter measurement and recording, automatic and manual report generation, contingency evaluation, emergency action execution, and more, under one umbrella. An EMS replaces a host of legacy systems used to monitor, control, troubleshoot, and record electrical network parameters and components.

Legacy systems have typically comprised annunciation panels with indication lamps and horns, hardwired alarms/controls, transducers, auxiliary relays, and log sheets. Plant electrical networks were usually controlled and monitored by systems confined to the associated substation. Users had to necessarily prioritize the sections of the network that required remote control and monitoring. Other main drawbacks associated with legacy systems include lengthy downtimes, maintenance and troubleshooting difficulties, and the operator-centric nature of the systems with the unavoidable possibility of human error.

Several factors have converged to make the modern EMS possible:

- The rapid advancement in industrial electronics
- The invention of the personal computer (PC)
- A significant increase in performance
- A dramatic drop in component prices

The earliest EMSs consisted of mainframe computers that were costly, bulky, and hard to program. External devices were initially hardwired back to the computer. Then a distributed format evolved that used multiplexed signals over a common wire or over the electrical distribution system (power line carrier). The latest EMSs use intelligent electronic devices (IEDs), which are relays capable of communicating a wide range of data over a dedicated line or network.

The evolution and widespread use of IEDs over the last two decades have made it easier to implement a comprehensive control and monitoring system. IEDs can also monitor the status of the associated electrical system. The combination of digital (status monitoring and control) and analog (real-time) measurements gives the IED a snapshot of the state of the associated part of the electrical network at any given point in time. There has also been considerable enhancement in the communication interfaces available in IEDs that allows measured/monitored values to be transferred to a remote location within an acceptable duration, thus allowing remote, near-real-time electrical system monitoring. Hence, it is possible to provide a central control and monitoring system by building upon the capabilities of these IEDs.

Along with IEDs, other developments have contributed to the efficiency and effectiveness of current EMS technology. Software evolution and communication platform standardization ensure that remote/field IEDs can be programmed, multifunctional displays created, and software functions assigned quickly and efficiently from the CCR, often with little more than drag-and-drop effort. The evolvement of industrial Ethernet and wireless technologies has made it possible to connect to automation systems from remote locations and transmit large amounts of data at high speeds. And management information systems (MISs) are now also built into most EMSs.

EMS REQUIREMENTS FOR THE NEW REFINERY

The switchyard, main substations, and process substations of the new refinery are geographically separated by distances varying from 1 to 3 km. Hence, a central EMS was needed to deliver a consistent, unified system of operation, monitoring, and reporting.

The key advantages offered by any EMS are:

- Centralized monitoring and control
- Prompt fault reporting, easy trouble-shooting, and faster decision making
- Flexible configuration
- Analysis on a common time domain
- Interoperability among different devices
- Distributed intelligence

It was also envisaged that the new refinery's EMS would be designed to accomplish the following specialized functions:

- Interface with the earlier-generation EMS of the old refinery to acquire selected network information
- Carry out selected control and contingency actions in the old refinery's electrical network when both networks are operating in parallel
- Interface with third-party control and monitoring systems

Functionalities Required in the New Refinery's EMS

The new refinery's EMS (see **Figure 2**) was envisaged as being the central point for controlling and monitoring its electrical network. To meet this objective, the EMS needed to provide the following main functionalities:

- Control and monitoring of the new refinery's medium voltage (MV) and low voltage (LV) switchgear
- Control and monitoring of the new refinery's 220 kV switchyard and two 33 kV substations (which have gas-insulated switchgear [GIS]) via an SAS
- Main and backup load shedding for the new refinery's electrical network
- Unified load shedding when the electrical networks of both refineries operate in parallel
- Tie-line control (active/reactive power control over the inter-refinery tie lines)

The new refinery's EMS was also required to possess the following features:

- Interface with other refinery control systems
- Interface with other monitoring systems (video wall, corporate local area network [LAN], and disturbance recording system [DRS])

Key Design and Performance Aspects Established for the New Refinery's EMS

The technical specification document for the EMS evolved out of a continuous process of interaction among the project engineering teams (from Bechtel and Reliance) and the end user (new refinery operations and maintenance teams).

An EMS offers centralized monitoring and control, prompt fault reporting, easy troubleshooting, faster decision making, flexible configuration, analysis on a common time domain, interoperability, and distributed intelligence.

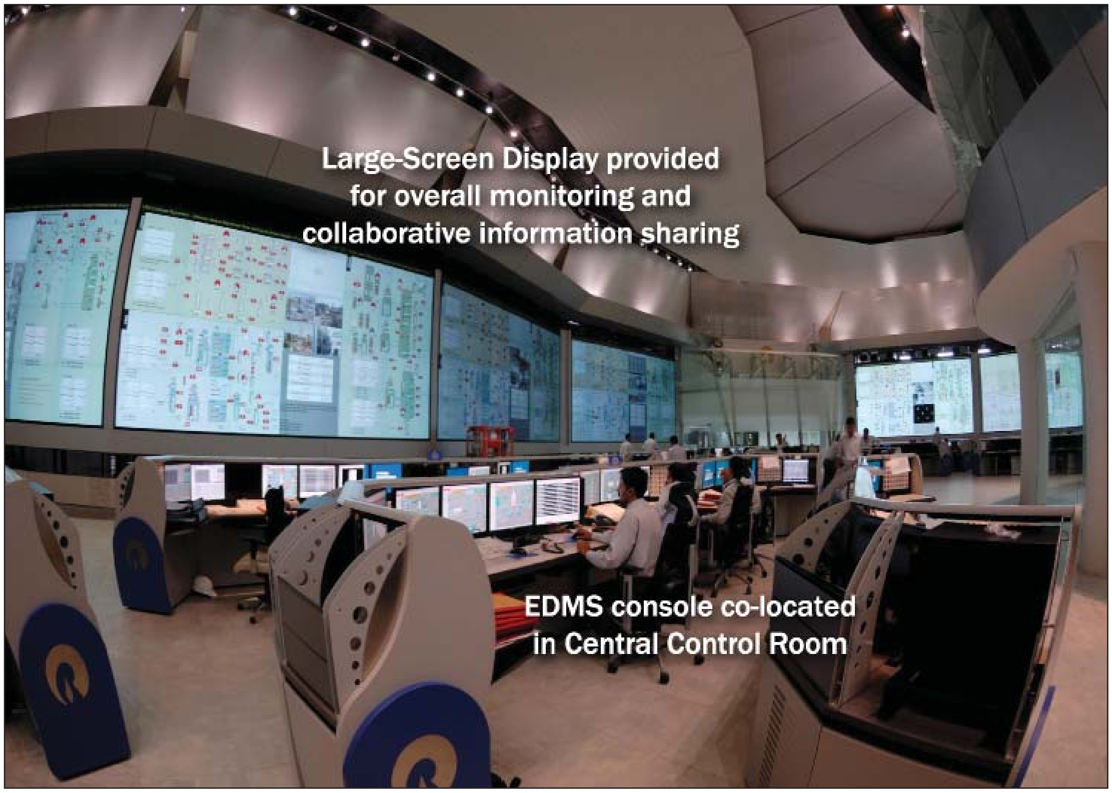

Figure 2. New EMS Setup in Jamnagar CCR

Rather than build on the old refinery's nearly decade-old EMS, it was decided to start from the basics in preparing the technical specification for the new refinery's EMS.

Rather than build on the nearly decade-old design and operation of the old refinery's EMS, it was decided to start from the very basics in preparing the technical specification document for the new refinery's EMS. The following key requisites were reflected:

- EMS functionalities that incorporate valid end-user requirements, which include the functionalities available in the old EMS, additional functionalities to overcome the limitations of the old EMS, and specific functionalities necessary to oversee and control the extensive inter-refinery electrical network
- Use of the latest applicable technology and hardware to ensure that the EMS is suitable for the anticipated expansion of the electrical system over the next 10 years without major hardware or software modifications
- Incorporation of lessons learned from the old EMS in terms of equipment selection and application engineering

The whole process of formulating, reviewing, and finalizing the EMS technical specification document took approximately 3 months. The following key design points were emphasized in this document and during the bid evaluation process:

- ***An "open" system*—**Open industry-standard communication protocols, programming languages, and graphics design systems were to be used insofar as possible. The operator workstations were to be based on the Microsoft Windows® XP operating system and enable operators to interact with the system easily. This would ease the process of further EMS expansion, modification, and enhancement.
- ***System redundancy*—**Redundancy was specified at the various levels of the EMS (i.e., server redundancy, processor redundancy, and communication network and associated element redundancy) so that failure in any part of the EMS would not affect overall operation. All key network elements (server and communication links) were to be monitored for physical condition. The EMS also had to incorporate data consistency check and data validation packages to detect failure in any part. Furthermore, the EMS was to be built with hot-swappable components insofar as possible to achieve the highest system availability and lowest downtime during repairs.
- ***Separation of critical functions and distributed intelligence*—**Although the EMS was to function as one single unit, it was to be internally divided into independent subsystems such as control, monitoring, load shedding, IS&R, control room, and third-party interface. With this configuration, overload or failure of any one subsystem would have minimal or no effect on the operation of the other critical functionalities.
- ***Enhanced human-machine interface (HMI) and help tools*—**HMI graphics were to use the "object" and "aspect" concept, where each piece of equipment (e.g., circuit breaker, generator, transformer) is identified as an "object" and each "object" has various "aspects" (e.g., control faceplates, alarm lists, trends).
- ***System reliability and availability*—**To validate that the EMS was proven and reliable, the vendor was to provide calculations demonstrating that it was designed to have a minimum availability of 99.99%. The EMS was also to be equipped with software to continuously monitor server and communication link operation and report any hardware/software errors.
- ***Suitability for further expansion*—**A number of key features were specified to ensure that the EMS could be augmented to cope with the new electrical network: the latest generation of controllers and processors; scalable server, database, and communications link architecture; sufficient spare server/workstation memory and communication link capacity; and an adequate number of installed spare input/output (I/O) ports. It was also specified that the EMS should allow processors to be replaced or upgraded to increase computational power and expand the system without requiring system or application software changes.

Additionally, the following key performance parameters were also specified:

- Under transient conditions, it may be necessary to shed loads to match operating load to available power generation. Based on the results of system studies, the load-shedding process had to be completed within 80–120 ms. As a backup, an under-frequency load-shedding system (UFLS) was also to be provided that could complete load shedding within 200 ms.

- Limits were set on the controller and remote terminal unit (RTU) loadings under steady-state and abnormal (transient) conditions to ensure that the EMS would continue to function normally under all electrical system operating conditions.
- Performance limits were set for the data update times at outstation nodes, display update times at the CCR, command execution times, automatic changeover times between controllers/processors/servers upon failure, etc.

TECHNOLOGY SELECTION FOR THE NEW EMS

Being a critical system aimed at avoiding power blackouts and optimizing electrical network operation, the new refinery's EMS was subject to a technology selection process carried out based on the dominant functional requirements vis-à-vis the latest industrial practices/trends. During this process, the EMS solutions offered by the four primary EMS bidders were evaluated against the following key criteria:

- What EMS functions were key to the proper functioning of the overall refinery?
- What errors/failures within the EMS would render any given EMS function unavailable?
- What components/devices within the EMS were required to support each EMS function?

Based on the design and performance aspects described in the previous section of this paper, the following attributes were used to evaluate the various EMS offers:

- System architecture
- Proven hardware and application technology
- Structurally developed and thoroughly tested modular software
- Reliability and availability
- Ease of maintenance
- Scalability for future expansion
- Availability of integrated supervision and diagnostic functions for modules and systems
- Competency of supplier's onshore resources to support the EMS
- Compatibility with third-party systems
- Compliance with codes and standards
- Analysis of failures reported on similar projects and the solutions deployed by the supplier to overcome them

After a rigorous evaluation process, ABB was selected as the supplier for the new refinery's EMS. ABB's EMS was based on its advanced System 800xA technology and was one of the largest power management systems supplied by ABB in the world. Furthermore, ABB had also supplied the old refinery's EMS and was involved in the various expansions of that refinery. Hence, selecting the ABB EMS was also expected to ease the process of interfacing the two systems.

ABB's EMS was based on its advanced System 800xA technology and was one of the largest power management systems supplied by ABB in the world.

DESIGN AND CONFIGURATION OF THE NEW REFINERY'S EMS

The new refinery's EMS is configured to provide data acquisition, control, and monitoring for the facility's electrical network and to facilitate load shedding for both the new and the old electrical networks (see **Figure 3**).

The EDMS caters to data acquisition, selected circuit breaker control, and electrical generation and distribution system monitoring. The LMS

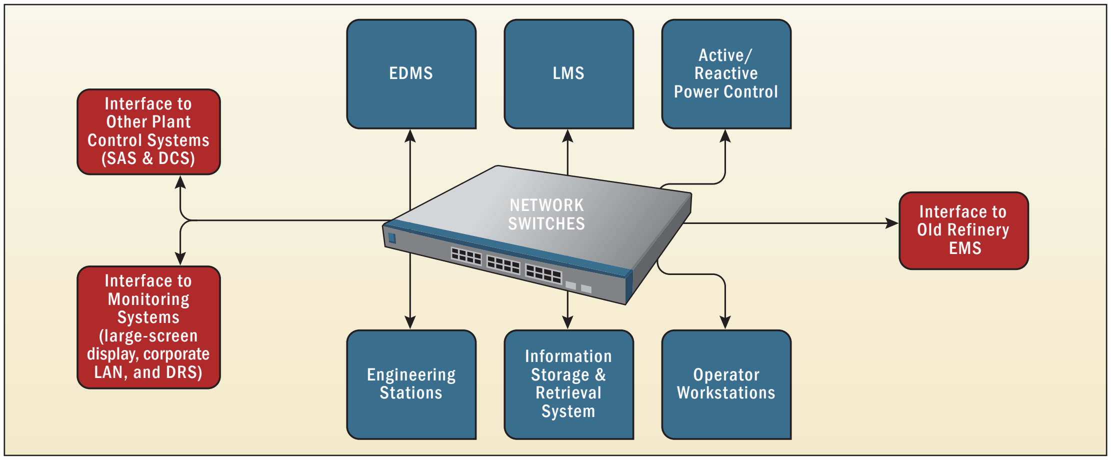

Figure 3. Overall Configuration of New Refinery's EMS

handles load-shedding functionality, generation control, and tie-line control.

The EMS includes approximately 50,000 I/O points (hardwired and soft).

The new refinery's EMS includes approximately 50,000 I/O points (hardwired and soft).

Topology

The EMS consists of a group of CCR servers connected to the EDMS and LMS nodes in the new refinery's substations. **Figure 4** shows the CCR equipment arrangement.

The CCR servers include:

- Domain servers
- Aspect servers for object presentation
- Connectivity servers that interface with ABB's AC 800M controllers in each substation for further interface with hardwired I/O and intelligent meters
- Connectivity servers that interface with ABB's COM 500 RTUs in each substation for further interface with the Siemens SIPROTEC IEDs used in the new refinery's EMS
- IS&R servers with modular smart array (MSA) units

The CCR servers are redundantly configured to ensure continuous availability and reliability under all conditions.

Each pair of connectivity servers (in redundant configuration) can have a logical connection to 20 nodes. Since 36 AC 800M controller nodes and 22 COM 500 RTU nodes are distributed among the various substations, three pairs of connectivity servers were provided to interface with the controllers and two pairs were provided to interface with the RTUs. This ensures that sufficient spares remain available for the future electrical network expansion.

In designing the HMI graphics, ABB used its Aspect Objects™ technology, wherein each piece of equipment (e.g., circuit breaker, generator, transformer) is identified as an object and each object has various aspects (e.g., control faceplates, alarm lists, trends). Aspects are picked from the aspect servers, while the live data from these aspects is picked from the connectivity servers. Alarms and events are generated at the operator stations (OSs) to provide alerts in case an object is in an abnormal state.

A master clock in the CCR obtains global positioning system (GPS) time references and

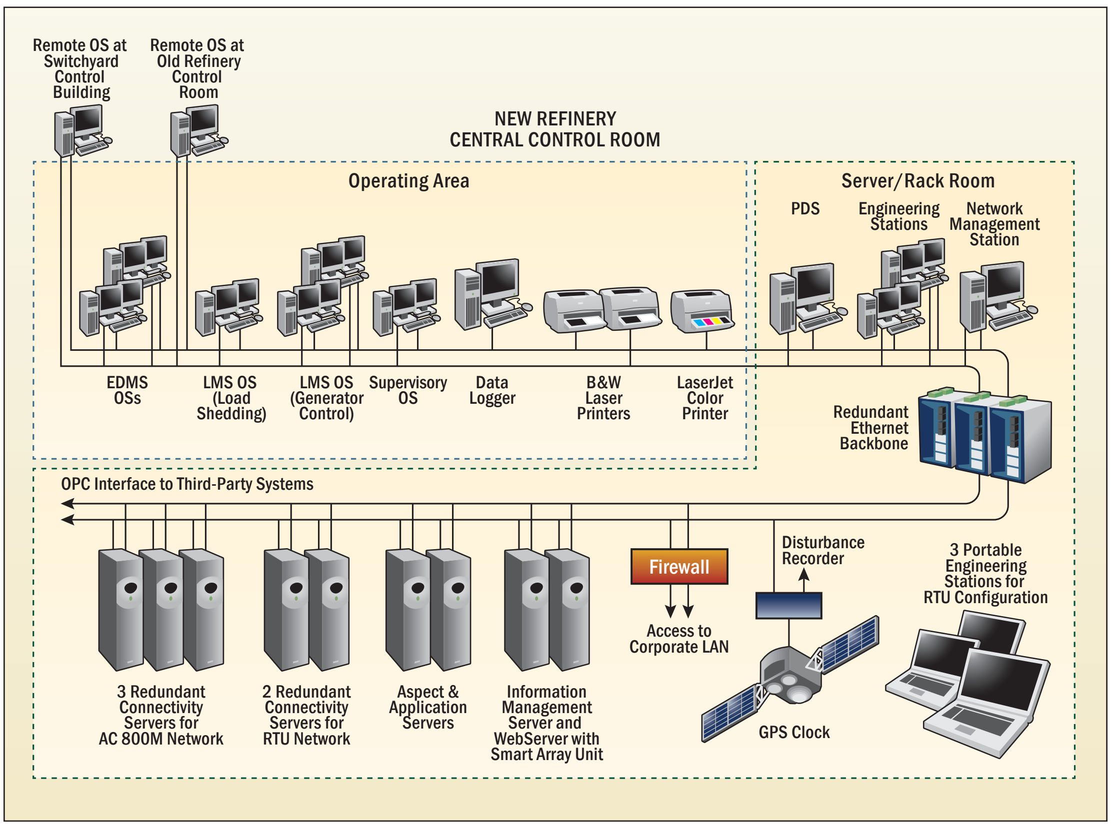

Figure 4. EMS Configuration in the CCR

periodically synchronizes the clocks in the various controller and RTU monitoring modules. This provides a common time baseline across the electrical network for analysis of events and alarms after any disturbance.

The CCR also houses the operator monitoring and control workstations, as well as engineering stations for modifying the EMS applications, incorporating new substations into the EMS network, etc. All workstations that interface with the EMS are connected with the EMS servers via client/server technology on redundant networks.

Web servers and firewalls allow selected EMS parameters, such as log files and reports, to be viewed on the corporate office LAN.

A data logger collects and stores all events from the EMS.

A standalone program development and testing system (PDS) in the CCR server rack room is used to develop, modify, test, and prepare future programs offline before incorporating them into the EMS.

Redundant Ethernet switches in the CCR provide connectivity between the various components of the EMS. A network monitoring station monitors the complete Ethernet network and associated elements of the EMS from the CCR. All diagnostic features configured for communication interface can be viewed from the CCR.

Four main networks within the EMS interconnect the various EMS devices:

- ***Control network for AC 800M controllers***—This network interconnects all EDMS and LMS controllers and is connected to AC 800M connectivity servers. The network facilitates the transfer of status data, control data, and measurement data (current, voltage, MW, and MVAr) for the EDMS.
- ***Control network for COM 500 RTUs***—This network interconnects the EDMS RTUs located at different substations and identified for interfacing with the individual substation IEDs. The network is connected to COM 500 RTU connectivity servers and facilitates the transfer of status and measurement data from the IEDs for the EDMS.
- ***Refinery HMI network***—This network interconnects, via EMS network switches, all operator workstations, servers, and printers identified for the function of providing operator and engineer interaction with the EMS.
- ***VIP network***—This network communication link is used to transfer time-critical data related to load shedding from one controller to another via a dedicated network. The network is connected to the AC 800M controllers to enable communication between the selected load-shedding controllers.

The EMS continuously monitors the operation of the EDMS/LMS nodes and its own communication links and reports any hardware/software errors to the EMS servers. These system events can be viewed from the OSs. The EMS also checks for errors/failures in processors, communication links, converters, and I/Os. The EMS facilitates failure isolation and correction and includes features that promote rapid fault isolation and online component replacement.

Four main networks within the EMS interconnect the various EMS devices.

Electrical Distribution and Management System

The EDMS nodes collect substation data from IEDs (via serial link) and hardwired I/Os and perform control commands issued from the CCR OSs. EDMS nodes in main substations also facilitate load-shedding functionality by transferring relevant data to the load-shedding controller.

Each EDMS node comprises two subsystems:

- ***COM 500 RTU subsystem***—Using International Electrotechnical Commission (IEC)-103 protocol, this subsystem provides a serial communication interface with the IEDs to receive selected data from them and send time synchronization messages to them. Sixteen loops are connected to a single subsystem to achieve the necessary performance specifications.
- ***AC 800M controller subsystem***—This subsystem interfaces with hardwired I/Os to collect digital inputs (e.g., circuit breaker status, circuit breaker service status, protection alarms) and issue hardwired control commands to circuit breakers based on commands from the operator in the CCR.

Since some of the process substations house a limited number of I/Os, these are provided with remote I/Os with process field bus connectivity over optical fiber cables to the AC 800M controller in the upstream main substation.

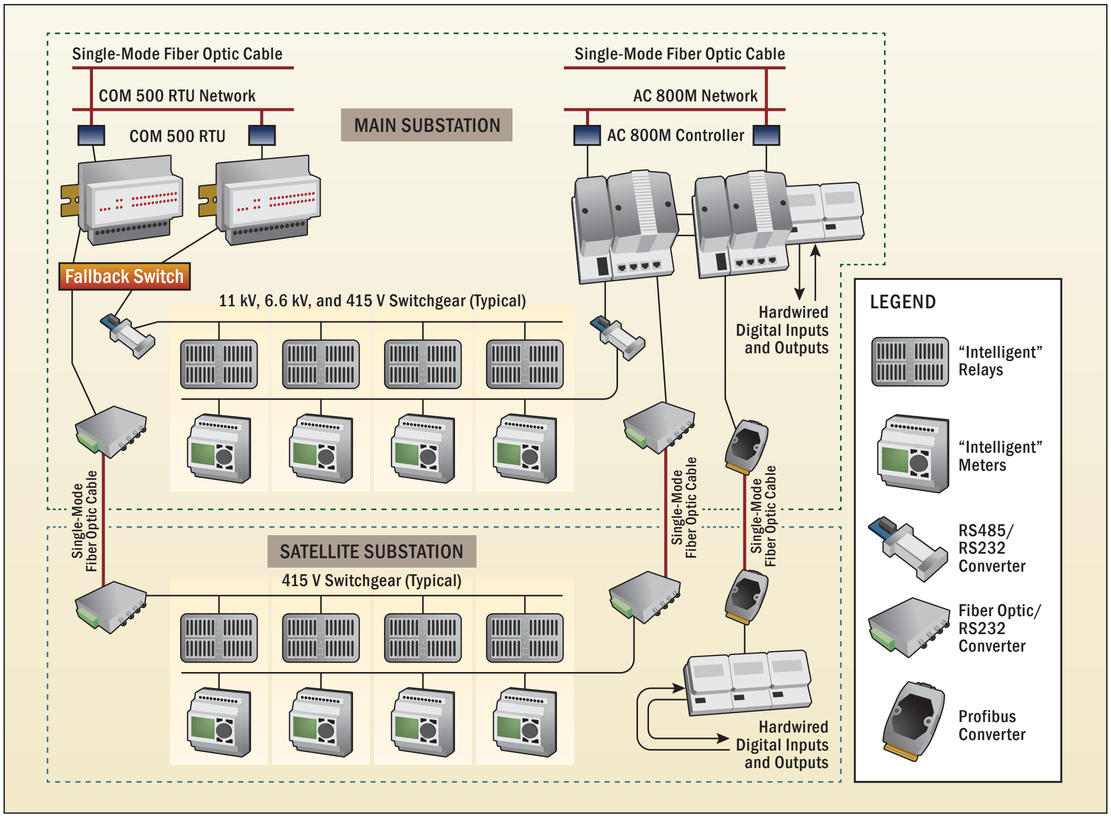

Figure 5. Arrangement of EDMS Nodes in Typical Process Substations

The arrangement of EDMS nodes in typical process substations is shown in **Figure 5**.

The EDMS nodes also carry out sequence-of-events (SOE) reporting. In addition to the normal status reporting of hardwired inputs, any status input point may be assigned to SOE reporting. The EDMS nodes detect changes in the state of SOE points and record the date and time of change with a resolution of 0.4 ms. The time tagging of all SOE inputs within a substation is synchronized to ensure that SOE inputs connected to different control cabinets maintain the same time resolution and accuracy.

The EDMS node located in the 220 kV switchyard control room interfaces and communicates with the switchyard's SAS via IEC-104 protocol. The SAS connects with the switchyard's IEDs via IEC-61850 protocol. The EDMS communicates with the switchyard SAS to obtain switchyard bay monitoring and control data.

Displays in the EMS give the operator a total overview of the new refinery's electrical network. Network status, measurements, and alarms are available as part of the display, which includes the following main categories:

- Single-line diagrams for overview and control
- Trend displays to monitor measured value against history
- Alarm displays
- Event displays
- Help displays
- Report displays

The displays are automatically updated with the latest tag data approximately every second.

Main Load-Shedding System

Overview

Load shedding becomes imperative when electrical load demand exceeds available power after power source loss or network disintegration (i.e., formation of one or more islands within the electrical network when network circuit breakers open). The load-shedding system has to ensure the availability of electrical power to all essential and most critical refinery loads. This is achieved by switching off nonessential loads when there is insufficient power in the network or parts of it.

When the new refinery's main load-shedding system (MLS) is triggered by the operation of a critical input that results in power source loss or network disintegration, the system calculates network power balances by subtracting electrical loads from available power. If the

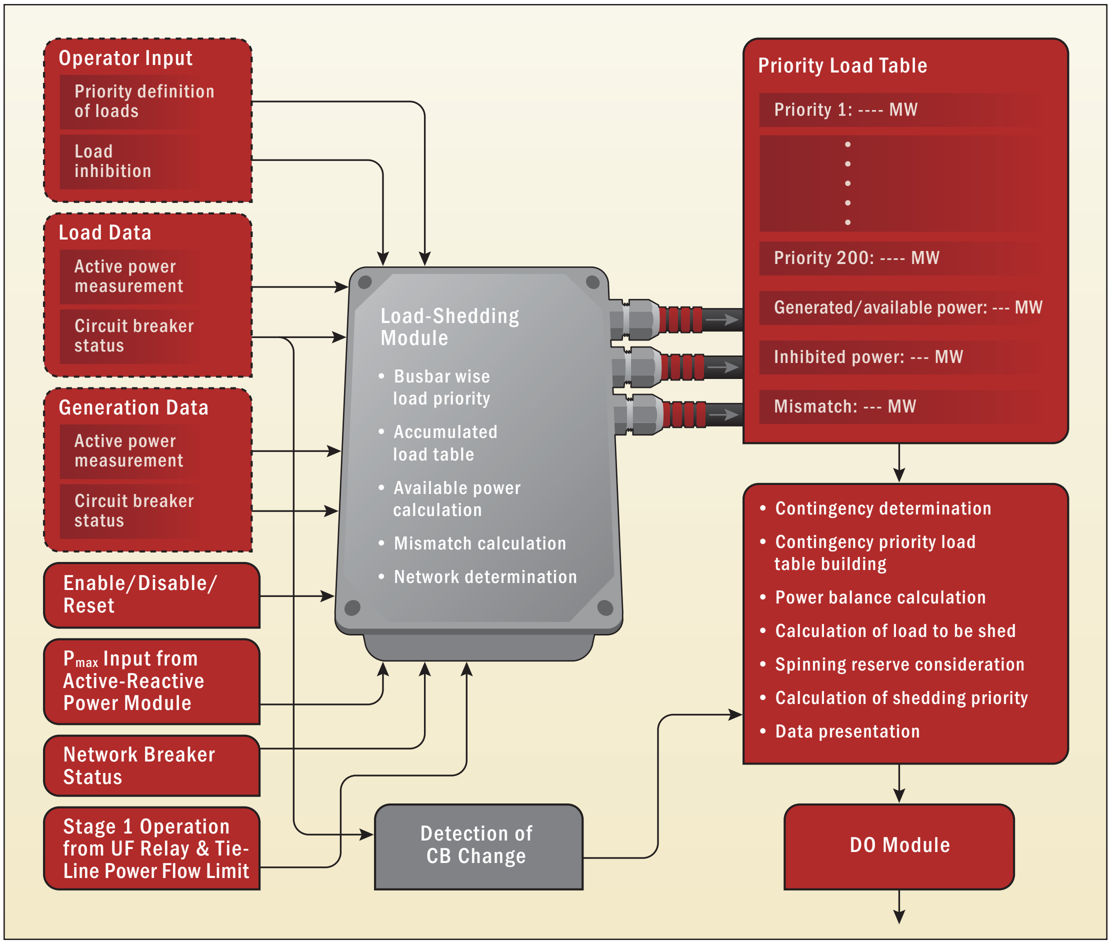

Figure 6. Main Load-Shedding System Logic

The load-shedding system ensures the availability of electrical power to essential and critical refinery loads by switching off nonessential loads when there is insufficient power.

power balance calculation is negative, there is a power deficit. The power deficit is compared to a priority load table, low priority loads are identified, and load-shedding commands are issued to them. The MLS logic incorporated into the EMS is shown in **Figure 6**.

Operator Input

Each load feeder has been prioritized on a scale from 1 to 199, with 1 being lowest priority (first to trip) and 199 being highest priority (last to trip). A graphic display allows operators to enter priorities for each switchboard; **Figure 7** shows a typical example.

The load-shedding system automatically groups loads having the same priority.

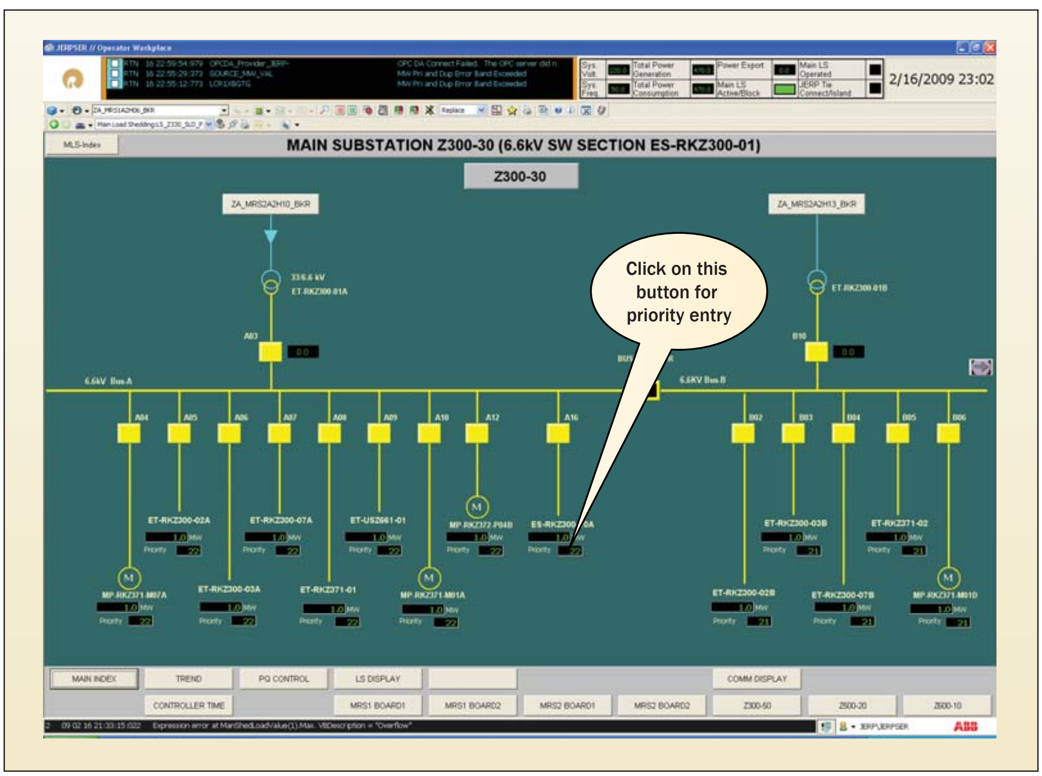

Figure 7. Setting Load-Shedding Priorities

Operators are able to inhibit any feeder/group from main load shedding if necessary for a given operating scenario.

Processing

The main load-shedding controller builds a priority load table for each load busbar. A load busbar is any part of the electrical network that has generation and loads connected. The table also includes the total active power available from the generators connected to a particular load busbar and the accumulated value of the loads pertaining to the same load busbar.

The network determination module determines the connectivity of every load busbar based on the status of critical breakers. The result is used to integrate the load busbar priority load tables into contingency priority load tables.

The values in the contingency tables are used in the following formula to calculate the power balances for all contingencies:

$$P_{\text{To be shed}} \text{ or Power Balance} = \text{Total Available Power} - \text{Total Load}$$

where total available power equals the summation of the actual generator output values and the spinning reserve connected in the existing contingency.

To add a margin of safety and maintain electrical network stability at all times, when the power balance calculation is negative, the calculated power deficit is multiplied by an engineer-settable safety factor before it is compared to the priority load table.

To guard against measuring circuit errors, the megawatt values used for the power balance calculation are obtained from two independent sources, and a validation check is carried out on the measured values before they are used in the power balance calculation. The power balance calculation is performed using 2-second-old data to prevent the load-shedding system from using analog data obtained while the electrical network is in a transient condition immediately after the occurrence of a critical event.

Output

The amount of load to be shed is calculated by comparing power deficit to the priority load table. The result of the comparison is used to generate load-shedding commands. For faster response time, these commands are distributed via dedicated virtual links (the virtual Internet protocol [VIP] network) to the various nodes that house the digital output (DO) modules that execute the commands and trip the load feeders.

When the MLS is not in service or fails to operate, the new electrical system's UFLS sheds loads based on drops in system frequency, which indirectly reflect network power deficits.

Under-Frequency Load-Shedding System

Overview

The new refinery electrical system incorporates a UFLS as a backup to the MLS. When the MLS is not in service or fails to operate, the UFLS sheds loads based on drops in system frequency, which indirectly reflect network power deficits.

The UFLS is active only when the new refinery's electrical network is working in standalone mode, i.e., not tied into the old refinery's electrical network. When the tie lines between the two refineries are connected, the UFLS is automatically deactivated.

The under-frequency relays installed on the two 220 kV bus sections monitor under-frequency condition and rate of frequency drop (df/dt). Whenever these two parameters fall below their set limits, the corresponding under-frequency relay stage operates. This triggers the operation of the UFLS, which sheds loads based on comparing the amount of load identified for shedding against individual under-frequency relay stages and network conditions. The UFLS logic incorporated into the EMS is shown in **Figure 8**.

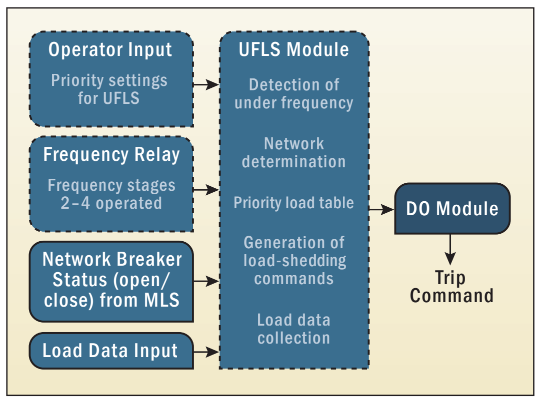

Figure 8. Under-Frequency Load-Shedding System Logic

Processing

Based on validated load data, respective load breaker status, and the positions of critical breakers, cumulative load tables are generated for the various contingencies that could arise for the equipment connected to each 220 kV bus section.

Various under-frequency relay stages are programmed with the under-frequency, df/dt, and time-delay settings. The load to be shed upon operation of any under-frequency relay stage is predetermined based on the results of transient studies conducted for various network contingencies that could occur.

Upon operation of any under-frequency relay stage, the load feeders to be tripped are identified by comparing the amount of load to be shed against the corresponding priority load tables.

Output

The amount of load to be shed is calculated by comparing power deficit to the priority load table. The result of the comparison is used to generate load-shedding commands. For faster response time, these commands are distributed via dedicated virtual links (the VIP network) to the various nodes that house the DO modules that execute the commands and trip the load feeders.

Unified Load-Shedding Scheme

When both refinery electrical networks are operating in parallel, it is vital to have an integrated approach to identifying the existence of power deficit conditions across them. It is also important to maximize load-shedding efficiency during parallel operation by shedding noncritical loads across both complexes during a power deficit condition.

Hence, a unified load-shedding scheme was developed and is enabled whenever the inter-refinery tie lines are closed. This unified scheme enables power deficits to be calculated for any source loss throughout both networks. When a power deficit condition is identified, noncritical loads are shed in either network based on predefined priorities across both.

During this scenario, the load-shedding system specific to each network is barred from shedding loads. However, if the unified network disintegrates (i.e., if the inter-refinery tie-line circuit breakers open or a section of a network operates as an island), the load-shedding requirements for the power deficits in the individual networks or islands are handled by the individual refinery load-shedding systems based on individual load priorities.

The unified load-shedding scheme includes the following main functions:

- Determining tie-line connectivity
- Calculating unified load-shedding priorities
- Generating unified dynamic load-shedding tables
- Generating unified load-shedding commands

The operating principle of the unified load-shedding scheme (the power balance calculation) is similar to that of the MLS. Upon the occurrence of a contingency (loss of generation), the unified load-shedding scheme calculates the power balance in the unified network by subtracting the electrical loads from the available electrical power. If the calculation results call for load shedding, the unified load-shedding scheme calculates the load-shedding priority, which is then compared to the unified priority load table to generate signals to trip the noncritical loads.

Figure 9 shows a sample display template for the unified load-shedding scheme indicating the power outputs from the power sources of both refineries.

When both refinery electrical networks operate in parallel, it is vital to have an integrated approach to identifying power deficit conditions across them.

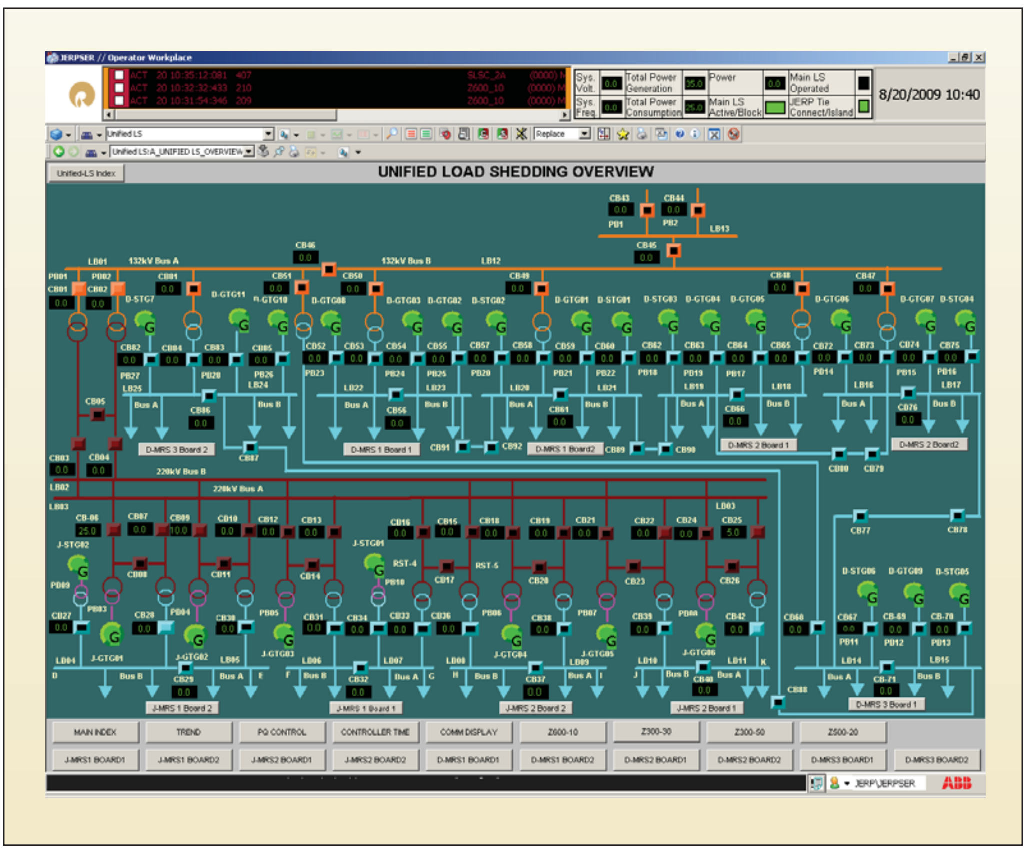

Figure 9. Sample Display Template for Unified Load-Shedding Scheme

P-Q control functionality provides GTG output control. When the inter-refinery tie-line circuit breakers are closed, the tie-line control scheme regulates the amount of active-reactive power flow between the two electrical networks.

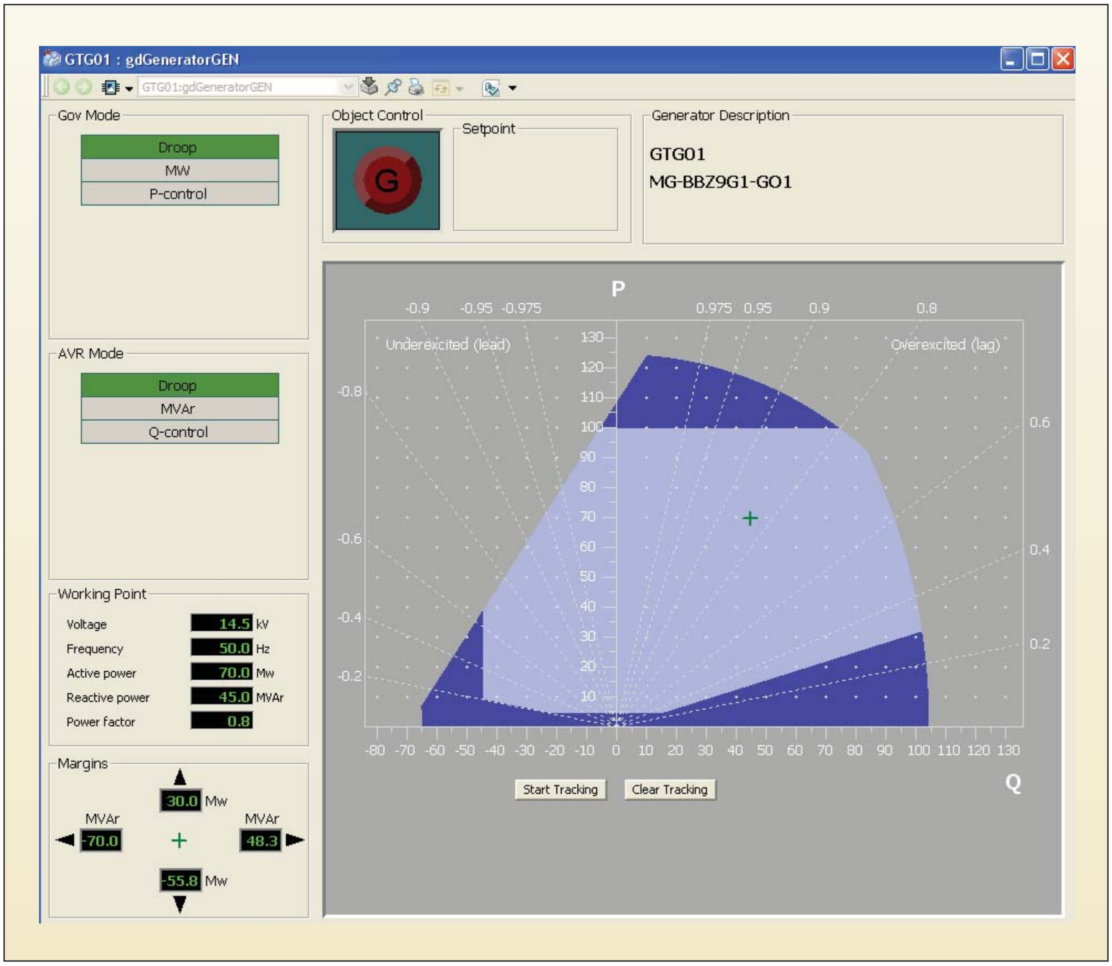

Figure 10. EMS Display for P-Q Control

Generator Control (P-Q Control)

P-Q control functionality within the LMS provides GTG output control. This functionality is provided by two control modules for each GTG:

- Active power control module
- Reactive power control module

These two modules operate independently of each other. The active power control module interfaces with the machine's local governor controller. The reactive power control module interfaces with the machine's local automatic voltage regulator (AVR).

Whether the LMS controls the machines depends on which control mode the operator selects. The machines can be controlled either locally (i.e., from the governor/AVR/generator control panel) or remotely (via the LMS).

When the point of control is local, no corrective actions are possible from the LMS P-Q controller. The following conditions must be fulfilled before generator control can be transferred to the LMS:

- The machine must be in speed-droop mode for governor control.
- The machine must be in voltage-droop mode for AVR control.

The P-Q control module governor/AVR set points can be adjusted from an OS by means of either a raise/lower command or a fixed load set point, as determined by the operator. **Figure 10** shows the LMS display for setting the P-Q control set points. The set points are displayed over the generator capability curve to give the operator a visually striking illustration of the operational margins available at any given set point.

Tie-Line Control

When the inter-refinery tie-line circuit breakers are closed, the tie-line control scheme regulates to a preset level the amount of active-reactive power flow between the two electrical networks. The new refinery's generators have a higher rating than the old refinery's, and the new refinery's electrical network currently has excess power under normal operating conditions. Hence, tie-line power flow is usually from the new network to the old one. The tie-line control scheme controls the active-reactive power generation of the new refinery's GTGs to maintain the active-reactive power flow between the two electrical networks at the level pre-set by the operator.

Information Storage and Retrieval System

The IS&R system provides centralized data collection, management, analysis, and presentation services for the EDMS and LMS. Because information is the key asset for these two systems, the IS&R system is designed to transform raw data into meaningful outputs, generate reports, and keep the data secure for future access.

The IS&R system provides automated capture of any defined EDMS and LMS data points, captures alarms and events generated in these systems, and securely stores the data.

The IS&R system can generate reports based on real-time data, historical values, or event information. These reports are available in two forms: user-defined and automated. The IS&R system can also generate energy balance reports for the new refinery's electrical network based on available historical data.

Interfaces with Other Third-Party Systems

The "Web interface license" residing within the IS&R server provides interfaces with third-party systems; examples of these systems are the corporate LAN network and the CCR large-screen video wall:

- ***Web interface with corporate LAN***—The EMS Web interface with the corporate LAN provides authorized users access to key information such as important displays, reports, and alarm/event data.
- ***OPC interface with CCR large-screen video wall***—The EDMS and LMS OPC interface with the large-screen video wall in the CCR enables critical data to be displayed. The information displayed is generally restricted to very high level data such as total consumed power, system frequency, various unit loads, tie-line power flow, 220 kV system overview, and generator status. A sample display template is shown in **Figure 11**.

The IS&R system is designed to transform raw data into meaningful outputs, generate reports, and keep data secure for future access.

MAJOR CHALLENGES ENCOUNTERED IN EXECUTING THE NEW REFINERY'S EMS

During project execution, a number of factory and onsite tests were performed to ensure the EMS's integrity and satisfactory operation. Test feedback was used to fine-tune the design to achieve the required system performance. The issues reported during testing were resolved in consultation with system experts and end users. The EMS hardware and application programs were also modified based on the results of these validation tests. Two of these modifications are discussed below.

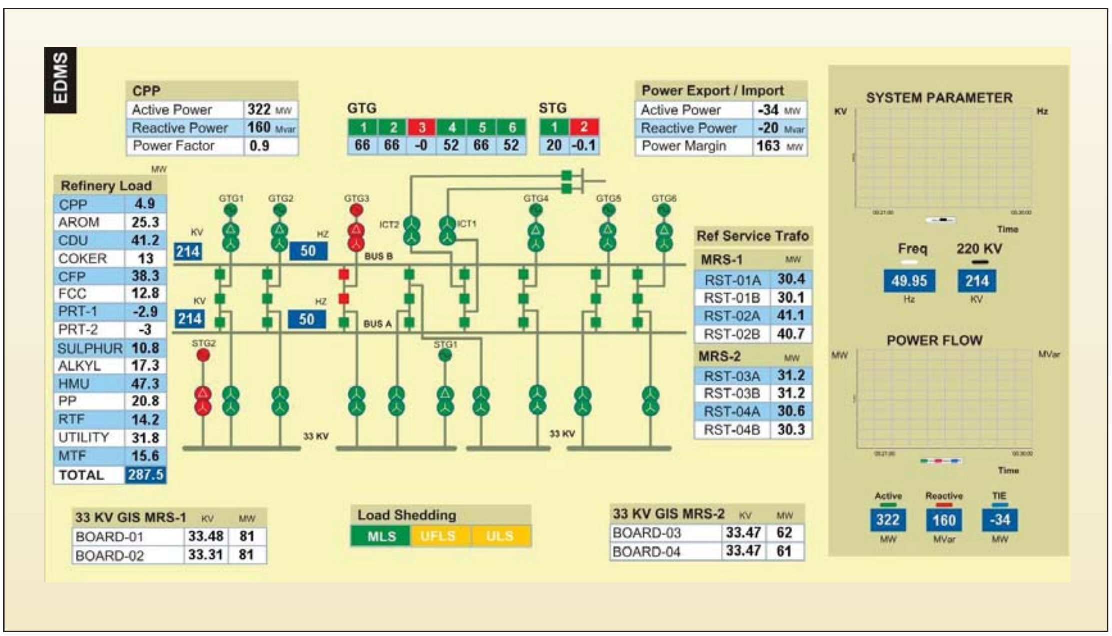

Figure 11. Sample Template for Displaying EMS Data on CCR Large-Screen Display

Segregation of Noncritical I/O Cards in the Main Load-Shedding System

During the design stage, the cards for both critical and noncritical I/Os associated with load-shedding were configured on a single AC 800M controller.

These I/O cards were all scanned at the same fast scan-time rate. However, scanning the analog (noncritical I/O) cards at such a high rate was not necessary for load-shedding purposes. Not all signals were time critical because the load-shedding system uses 2-second-old data to prevent load-shedding functions from using analog data obtained while the electrical network is in a transient condition immediately after the occurrence of a critical event.

During factory testing, it was observed that this all-inclusive fast-scan configuration prevented performance parameters (load-shedding operating time and processor loading) from being achieved. After further evaluation and discussions with experts, it was decided to introduce additional controllers to process noncritical I/Os at a lower scan rate. A high-end controller was introduced to process critical I/Os. It was also verified that adopting this solution would not significantly affect the overall project completion schedule.

Since controller loading and load-shedding performance are related to each other, various tasks executed by the AC 800M controller were also tuned to further optimize load-shedding performance.

While carrying out these modifications, care was taken to avoid changing the field cable terminations. A significant effort was also made to ensure that the changes caused minimal EMS application retesting.

All requisite performance parameters were achieved after the changes were implemented.

An EMS is very critical because it interfaces with practically all major electrical equipment. EMS philosophy development and procurement should be addressed early so that EMS detailed design can proceed concurrently with that of other critical equipment.

Sequencing the Under-Frequency Load-Shedding Application

During the site acceptance test for the UFLS, it was observed that the system was operated inadvertently in one of the simulated contingencies. This was a very serious condition, because inadvertent load tripping could lead to major production loss or even refinery shutdown.

To analyze the incident, the SOE and respective UFLS displays were observed and recorded. Based on this information, a similar condition was simulated offline so that the UFLS's behavior under this condition could be studied. This offline test confirmed that the system's behavior in the offline setup matched that of the real-time incident.

Further analysis revealed that the incident occurred due to an incorrect execution sequence programmed into a program/control module associated with the UFLS. This sequence was corrected, and the execution sequence of all programs and control modules connected to the system was checked in detail before the modules were redeployed in the EMS.

The EMS was subsequently successfully commissioned.

IMPROVEMENTS RECOMMENDED FOR FUTURE PROJECTS

The EMS is a very critical system for the entire electrical network because it interfaces with practically all major refinery electrical equipment. In developing the EMS for the new refinery, it was observed that EMS performance improvements sometimes necessitated adding or changing devices or modifying the design of other electrical equipment, including, in particular, critical items such as switchyard equipment, GIS, and MV/LV switchgear. Such adjustments are better coordinated when the initial EMS philosophy development and procurement activities are started sooner so that EMS detailed design can proceed concurrently with that of the other critical equipment.

Based on lessons learned, the following aspects need to be considered to improve EMS functionality on future projects:

- IEDs installed to monitor and control electrical networks should be based on IEC-61850, which facilitates interoperability, free configurability, and long-term stability.
- Optical fibers should be used for the IED network, even within substations, because they provide better reliability and reduce testing and commissioning efforts.
- The MLS and backup UFLS must be completely independent of each other in terms of hardware and application software.
- Detailed performance calculations for the processor that provides LMS functionality should be established in the initial project stages to avoid having to upgrade the processor and stretch the site acceptance test schedule during commissioning.

- After factory tests for a pilot or typical substation are completed, the test setup should be made available on site for repetitive engineering of EDMS functionalities (database population, display compilation, and testing). This helps optimize the engineering time cycle.
- Alarm and event management should be discussed in depth with the end user's operations and maintenance group and should be optimized during initial detailed engineering to avoid operational difficulties after commissioning. ■

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TRADEMARKS

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