System Islanding Using a Modern Decoupling System

Ameer Al-Mulla

Gulf Petrochemical Industries Company

Kamal Garg, Scott Manson, and Ahmed El-Hamaky

Schweitzer Engineering Laboratories, Inc.

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Abstract—The Gulf Petrochemical Industries Company (GPIC) plant in Bahrain produces ammonia, methanol, and urea. The GPIC process load is primarily steam driven; however, 24 MVA of critical loads are electrical, including the ammonia plant. One on-site combustion gas turbine is run in parallel to a connection to the local utility for a highly reliable power system configuration.

GPIC requires the ammonia and methanol plants to be islanded as soon as possible for external system disturbances. The loss of the ammonia plant for any reason leads to automatic shutdown of the entire petrochemical complex. The existing decoupling system misoperated once and had very limited system analysis capability. GPIC selected a new dual-primary redundant automatic decoupling system (ADS) to island their system for external system disturbances. Using the ADS, it is possible to analyze system events using the built-in tools of Sequential Events Recorder (SER) and event records, in addition to monitoring power system operating conditions. Since installation, the ADS has operated several times to island the GPIC system correctly for external system disturbances.

I. INTRODUCTION

Because of grave safety and financial consequences related to the uncontrolled shutdown of the Gulf Petrochemical Industries Company (GPIC) petrochemical facility, the critical loads are fed by a redundant power scheme. The GPIC facility uses a dual feed to the national grid owned and operated by the Ministry of Electricity and Water (MEW), as well as a 24 MVA combustion gas turbine (CGT) generator for redundancy. Either one of the feeders or the generator is capable of supplying the entire process electrical load. See Fig. 1; T114 and T115 are the redundant feeds, and MG6401 is the CGT.

The urea plant relies solely on power imported from the MEW national grid. The ammonia and methanol plants are normally fed from the CGT running in parallel with the grid connection. From a process point of view, the loss of the ammonia plant leads to the automatic shutdown of the urea plant. The electrical system is thus designed so that the loss of either the CGT or the MEW network is acceptable, but a loss of both sources results in the shutdown of the entire petrochemical complex [1] [2] [3].

The CGT has a history of sensitivity to disturbances in the national grid. To ensure the reliability of the GPIC network, a decoupling device was installed during the original commissioning of the complex in 1985. While only a single incident in a span of 22 years was attributed to the malfunction of the original decoupling device, GPIC proactively opted to replace the original device with a modern automatic decoupling system (ADS) that can cater to the ever-

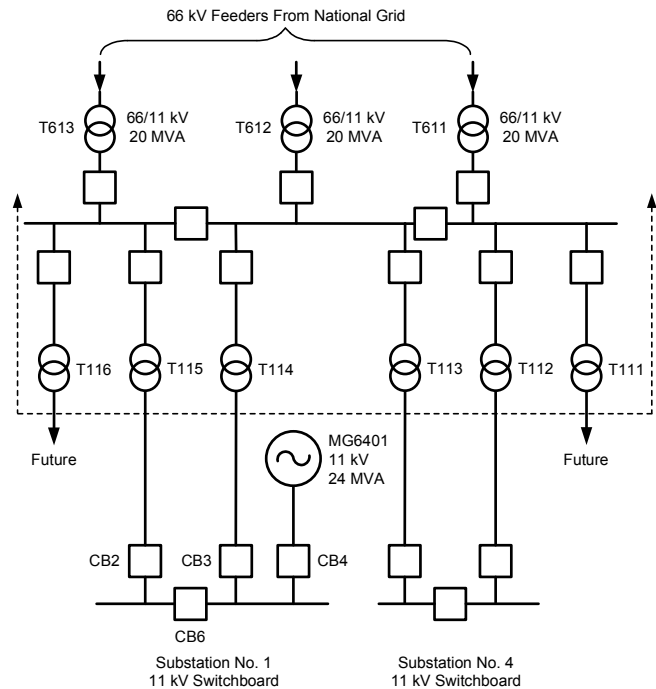increasing system disturbances emanating from the drastic expansion of MEW.

Fig. 1.   Feeding arrangement to petrochemical complex

The new ADS isolates (or islands) the GPIC CGT from MEW during external system disturbances. The system uses several protection elements to achieve this goal. Each of these elements and devices is explained in this paper. The new, state-of-the-art ADS also added several engineering diagnostic features that enable both operations and maintenance personnel to quickly diagnose and understand an islanding event.

II. THE POWER DISTRIBUTION NETWORK

The single-line diagram in Fig. 1 shows the feeding arrangement to the petrochemical complex. The 11 kV switchboard in Substation No. 1 feeds essential loads at the ammonia and methanol plants. The switchboard is supplied via two feeders (T114 and T115) and a CGT (MG6401), any of which are sufficient to supply all the power required at Substation No. 1 (approximately 15 MW).

During normal operation, the gas turbine MG6401 supplies the bulk load while the two infeeds from the national grid are kept at 0.5 MW each. The net 1 MW import keeps the

frequency deviation and process disturbance minimal in case of an opening of the utility ties. A guaranteed import of power also makes selection of a reverse power element pickup quite simple.

The new ADS trips Circuit Breakers CB2 and CB3 at the Substation No. 1 switchboard, islanding the most critical loads in the plant. The ADS monitors the current and voltages at T114 and T115, calculates quantities required for analysis, and initiates a trip to island the GPIC system based on the quantities monitored at the interface point.

On the other hand, the 11 kV switchboard at Substation No. 4 provides electrical power exclusively for the urea plant and relies solely on power imported from the grid (approximately 10 MW).

III. CRITERIA FOR REPLACEMENT OF THE DECOUPLING DEVICE

The initial automatic decoupling device was commissioned together with the power network in 1985. The original device provided basic protection against the following:

- Directional overcurrent
- Undervoltage
- Underfrequency
- Delayed overcurrent
- Instantaneous overcurrent

In 2007, the old device was replaced for the following reasons:

- Several near misoperations
- No diagnostics for device health
- Need for reliable power source for the whole complex
- Obsolescence of spares
- Need for improved monitoring and alarms
- Need for improved maintainability
- Facilitation of fault and operation analysis

The old decoupling device did not provide any system operation details, event report analysis data, system alarms, or Sequential Events Recorder (SER) reports. In the absence of such functions, it is difficult to analyze any disturbances or the system operation. The old decoupling device also did not communicate to supervisory control and data acquisition (SCADA) for information or control. It was not capable of providing new protection functions, such as phase angle and rate of change of frequency (df/dt). With the new ADS and digital relays, the protection systems are time-synchronized and have automatic archival of events (with analog and digital signals), continuous SER monitoring, and remote SCADA monitoring and control.

In 2010, GPIC will replace the open-delta potential transformer (PT) on the 11 kV switchgear with three-phase PTs. As part of this retrofit, the ADS logic has been modified to have the following:

- Directional overcurrent protection to isolate GPIC even faster
- Phase angle detection logic on a per-phase basis
- The ability to measure reverse power on each phase separately

More features were added to the logic for enhancements, such as enabling synchrophasors to detect df/dt and enabling a loss-of-potential feature to block all voltage protection elements in case of PT fuse failure conditions.

IV. HISTORY OF SYSTEM DISTURBANCES

System disturbances are common occurrences on the MEW network. The GPIC electrical system can become unstable or settle at a new set point after a disturbance is over. The GPIC system has a history of instability due to one or more of the following system disturbances:

- System fault
- Disconnect of any large load
- Trip of any large MEW generator
- Erroneous system operation or failure of control system
- Lack of reactive power (low system voltage)
- Reverse active power (low system frequency)

The disturbances are known to cause one or more of the following problems at the CGT and Substation No. 1:

- Unstable swing and out-of-step relaying trip
- Overwhelmed synchronous generator reactive power capability
- Machine overspeed/underspeed
- Turbine thermal limit protection
- Underexcitation
- Unnecessary motor load tripping
- Machine vibration trips

Some disturbances may also result in local plant mode, interarea mode, or control mode oscillations if corrective action is not taken. The GPIC system is connected via high-impedance, step-up transformers to the MEW system to reduce the fault current in the system. However, this results in a very large phase angle difference between the GPIC and MEW electrical systems. A reversal of power on the MEW intertie therefore can exhibit itself as a significant disturbance to the CGT synchronous generator rotor angle, further exacerbating the disturbance seen by the CGT.

Fig. 2 shows the equivalent two-machine model of the GPIC and MEW systems. Simplified power transfer equations are also indicated in Fig. 2. Power transfer between the two systems is dependent on the angle between the two systems in addition to other parameters (i.e., system voltages and impedance).

$$P = \frac{E_A \cdot E_B}{X_L} \cdot \sin(\delta_A - \delta_B)$$

$$Q = \frac{E_B}{X_L} \cdot \left[E_A \cdot \cos(\delta_A - \delta_B) - E_B \right]$$
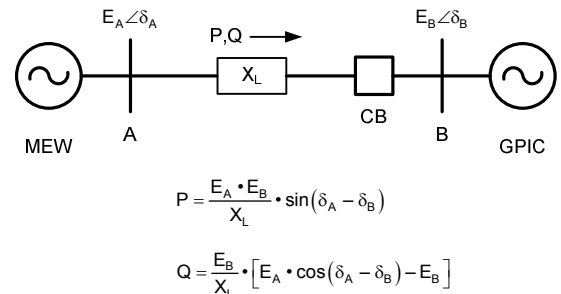
Fig. 2.   Simplified two-machine model

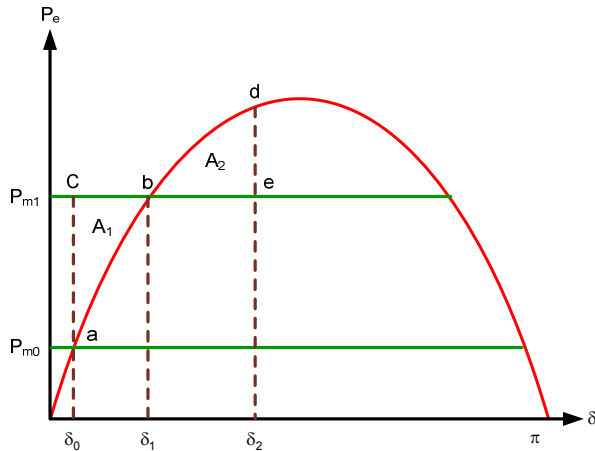Fig. 3 shows the power transfer at different machine internal angles.

Fig. 3. Maximum power and equal area

The system may settle at a different stable point if the system configuration changes because of system disturbance and if the system is properly damped. If the system is transiently unstable, it will cause large separation generator rotor angles, large swings of power flows, and large fluctuations of voltages and currents. This eventually leads to a loss of synchronism, resulting in large variations of voltages and currents [4].

V. SYSTEM DESIGN

A. Communications Architecture

Fig. 4 shows the communication between components in the GPIC ADS. Decoupling relays 51A and 51B (microprocessor-based bay control relays) are identical in functionality. Each relay simultaneously performs decoupling protection for both breakers; therefore, this is considered a "dual-primary" protection scheme [5].

The ADS includes an engineering station (labeled "computing platform"), which provides a graphical interface to view sequence of event (SOE) and oscillography (digital fault recording [DFR]) of system disturbances, alarms, and decoupling actions. All SOE and DFR data are archived on nonvolatile flash memory in the engineering station. The DFR recorded protection data include sampled currents and voltages, status of input/output contacts, relay elements, relay settings, and programmable logic stored in the relay at the time of the event.

System parameters, including voltage, MW, MVAR, frequency, equipment diagnostic alarms, and incident alarms, are monitored via a Modbus® communications link to the SCADA master. All devices (computing platform, communications processor, 51A, and 51B) are time-synchronized to the IRIG-B satellite clock for accurate time stamps.
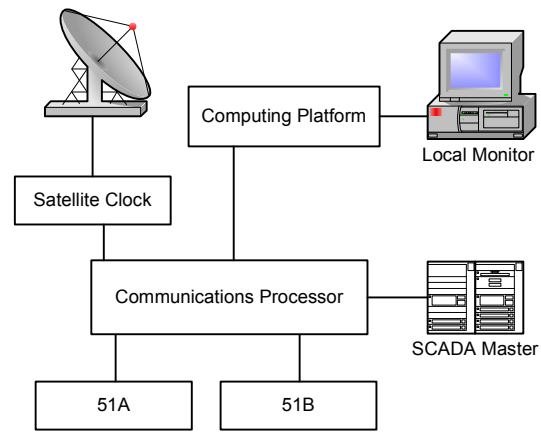

Fig. 4. Decoupling panel communications diagram

B. Protection Systems

The ADS provides system islanding based on the following elements:
- Phase angle deflection
- Reverse power
- Directional overcurrent
- Circulating current
- Undervoltage/overvoltage
- Df/dt operation
- Underfrequency/overfrequency

Both relays independently measure these quantities for both tie lines. The settings for each protection element are listed in Table I. Having three-phase PTs in the GPIC system allows for more sensitive settings of the phase angle element.

TABLE I
SETTINGS FOR THE DECOUPLING DEVICE

Protection Element	Alarm		Trip	
	Set Point	Time Delay	Set Point	Time Delay
Three-phase reverse power (when both breakers CB2 and CB3 are in service)	80% of trip	15 cycles	–1.0 MW	15 cycles
Three-phase reverse power (when only one of the breakers is in service)	80% of trip	15 cycles	–1.5 MW	15 cycles
Single-phase reverse power (when both breakers CB2 and CB3 are in service)	80% of trip	15 cycles	–0.5 MW	15 cycles
Single-phase reverse power (when only one of the breakers is in service)	80% of trip	15 cycles	–0.75 MW	15 cycles
Reverse overcurrent	No	No	65 A	10 cycles
Angle separation A-, B-, C-phase	6°	10 cycles	7°	10 cycles

As shown in Fig. 5, each relay has high- and low-side PT connections of both T114 and T115; this is for phase angle measurement. Now, a three-phase PT is available from GPIC and three-phase wye PT voltage from MEW. The phase angle set point is selected to detect the phase shift between GPIC and MEW on a per-phase basis. Phase shift due to wye/delta power transformers and load flow angle are also considered.
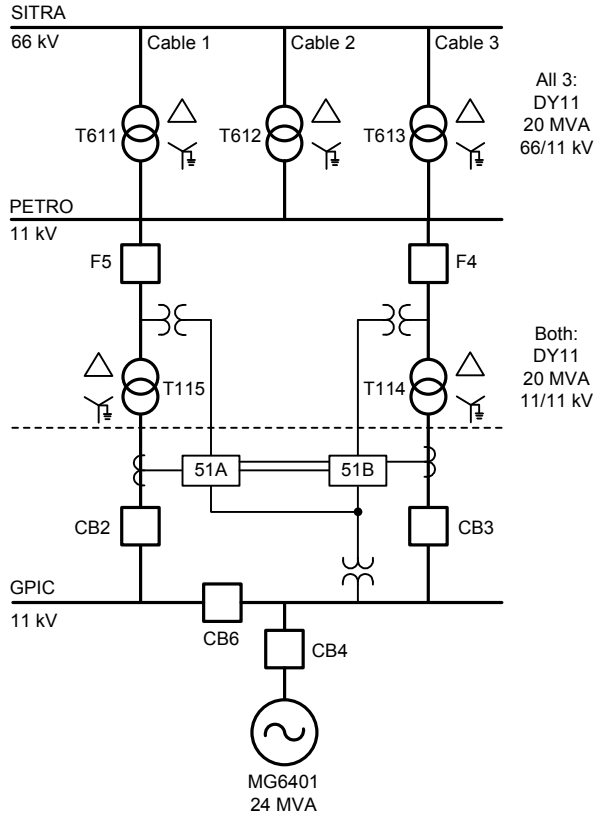

Fig. 5.   New ADS for GPIC

Based on if one or both tie breakers (CB2 and CB3) are closed, different settings for reverse power are selected (refer to Table I). The reverse power protection function is blocked for 60 cycles after the operation of any main breaker within the GPIC system, enabling the ADS to ride through any disturbances caused by GPIC.

Reverse power is assigned with two levels. GPIC can operate the system in two modes: when one interconnecting transformer (T114 or T115) at GPIC is in service or when both transformers at GPIC are in service. Reverse power flow monitored by the relay will be different depending on whether one or both transformers are in service.

Reverse MVAR is synonymous with circulating current protection and most commonly occurs during misoperations and failures of the load tap changer.

Tripping from the decoupling device is disabled when GPIC generation is out of service. Tripping is also wired in the block close circuit of GPIC Breakers CB2 and CB3. A trip to Breakers F4 and F5 indicates a trip to the MEW system, if MEW agrees to enable tripping based on the ADS. However, continuous monitoring of the decoupling device is also available to monitor and improve system performance by adjusting the settings. Protection logic is also programmed for the other protection functions using the freeform logic capability of the ADS.

Df/dt protection logic is set up with a combination of digital filtering and rated detection logic. No time delay was selected for the df/dt settings; rather, the filtering was adjusted to avoid spurious trips. Df/dt settings were selected to avoid system operation during system transients.

System trips and block close outputs from the relays are latched until manually reset by an operator, making the ADS act as a lockout relay.

Overfrequency protection is employed to decouple from MEW for a major loss of load on MEW. Df/dt detection was studied in detail for various system disturbances on the real-time system simulation.

Angle separation protection is the same as applying synchrophasor data to calculate the angle difference between GPIC and MEW in real time. With the advances in synchrophasor technology, it is also possible to calculate the damping factor and oscillation frequency using modal analysis to perform faster system islanding [6] [7].
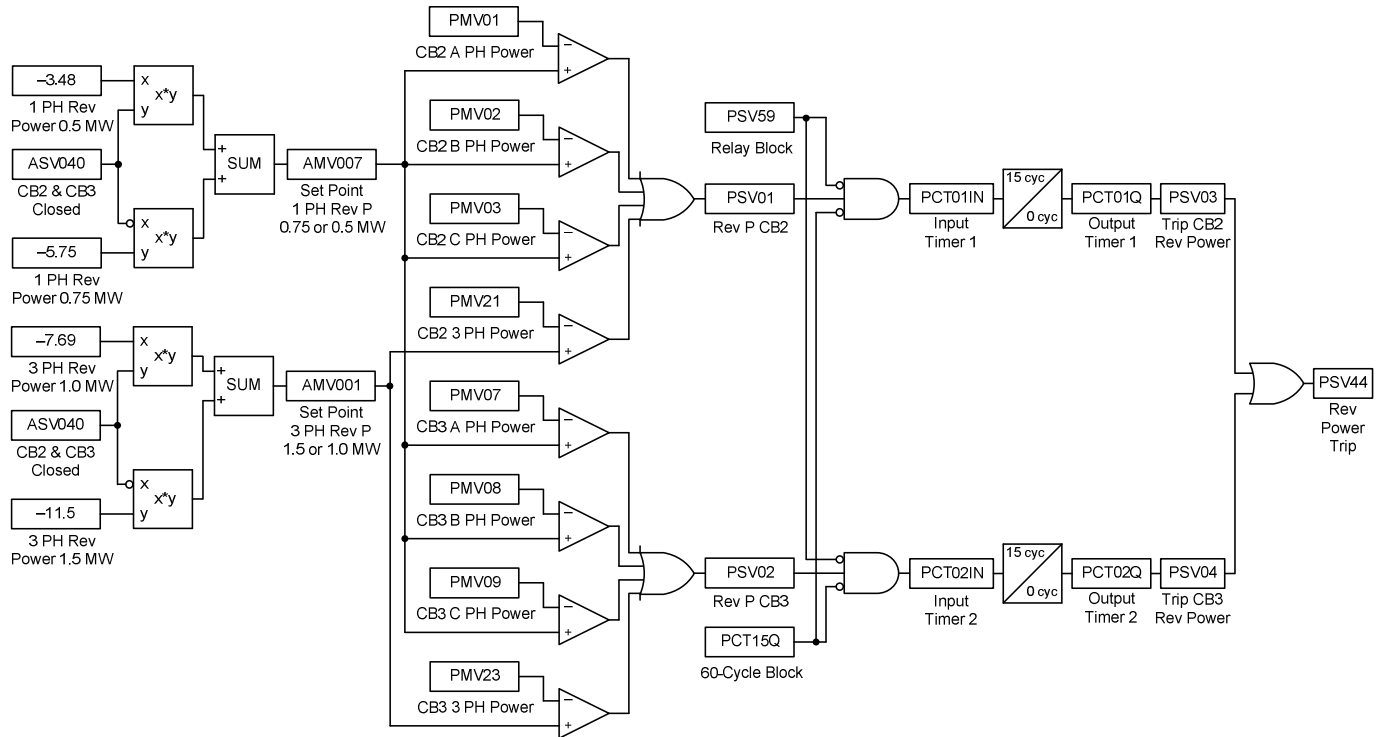
Fig. 6. Reverse power logic (refer to the appendix for terminology definitions and Section VII, Subsection C for a discussion of the selected settings)

Fig. 6 shows the reverse power logic for alarm and trip, programmed using the freeform logic capability of the ADS. For reverse power, the alarm set point is selected at 80 percent of the trip settings.

VI. SYNCHROPHASOR TECHNOLOGY

A. Introduction

Synchrophasor data allow us to determine the voltage and current phase relationship between multiple relays in different locations on a power system. Years ago, synchrophasor measurement capabilities were available only in standalone instruments called phasor measurement units (PMUs). In the last ten years, synchrophasors have become a standard capability of protective relays, meters, and recorders, as well as PMUs.

IEEE C37.118 has been widely accepted as the preferred method for exchanging synchrophasor measurement. Fast data rates are useful in observing the electrodynamic nature of the power system, such as power swings. Special-purpose computers called phasor data concentrators combine the streaming data from multiple sources to communicate the data to a central point for display, storage, or processing.

Locally, a system only needs a common time source, such as a clock, to synchronize all measurement devices. When more than one location is involved, Global Positioning System (GPS) clocks are a solution, because they can produce time signals accurate to a microsecond virtually anywhere in the world. Fig. 7 shows system voltages at different locations with the same time reference and provides a quick snapshot of the overall system.

In the future, the software installed on the ADS will provide a method to record and archive synchrophasor data in comma-separated value (CSV) and COMTRADE formats.

This software will be installed on the computing platform shown in Fig. 4 and will accept data from both the 51A and 51B protective relays, using IEEE C37.118 protocol.
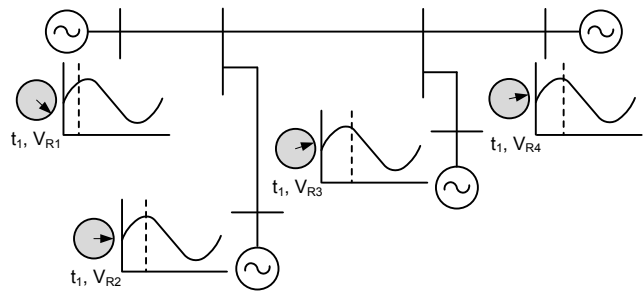

Fig. 7. Phasors with same time reference

B. Synchrophasor Future Application in GPIC

GPIC management wanted a future solution to monitor the MEW network voltage and frequency with a high sampling rate to identify and archive the sags and swells of voltage and df/dt. In addition, synchrophasor technology is also proposed to be used for future expansion of the GPIC plant, including new generation synchronization and control.

The proposed solution includes engineering station human-machine interface (HMI) screens to provide a snapshot of the GPIC system, as shown in Fig. 8. All relevant synchrophasor information will be automatically archived for future reference and any system disturbance analysis. This technology also provides continuous recording and archiving of df/dt.

The 51A and 51B relays have synchrophasors as a standard feature. Among many other signals, the synchrophasor df/dt element was configured to be recorded.

GPIC will use synchrophasors to monitor the MEW voltage waveform, and any sag or swell will be easily observed.
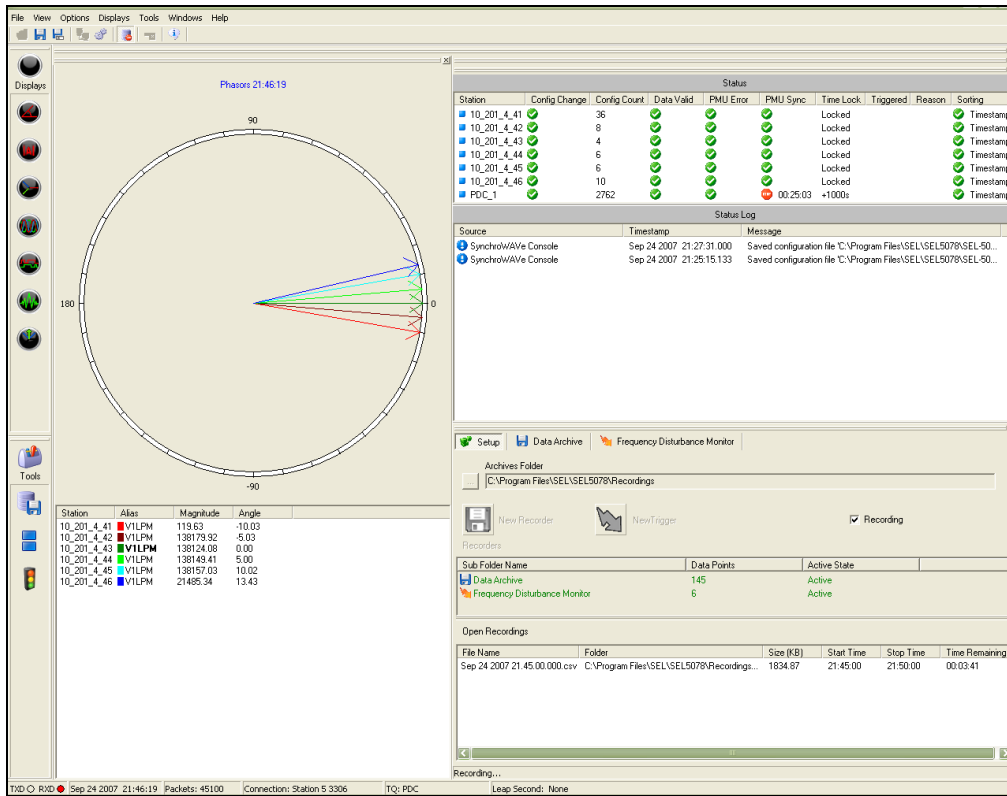
Fig. 8.   Synchrophasor snapshot

These data will be continuously recorded, compressed, and saved to a CSV file, and the data can be sent to an existing SCADA system.

Slower data rates, such as once per second or even less, are easier to communicate and process and are useful in directly measuring the state of the power system. This is better than state estimation, because it is simpler, costs less, requires less processing, has no convergence issues, is less dependent on system data, and is faster.

VII. SYSTEM MODELING AND VALIDATION

The scope of work discussed in this section includes:
- Model development
- Validation of ADS operation
- Live modeling validation

A. Model Development

A detailed power system dynamic model was prepared for the GPIC and MEW systems. A summary of the dynamic simulation model for the ADS is shown in Fig. 5.

Fig. 9 illustrates the GPIC and MEW system model built into the real-time digital simulation system. There are several generators in the MEW system near GPIC that require detailed simulation in the dynamic model. Two generators in MEW, G1 and G2, are modeled with detailed exciter and governor models. The G3 machine is modeled as the equivalent machine to represent the rest of the MEW system with an appropriately large inertia. The GPIC machine MG6401 is also modeled with detailed exciter and governor models to represent actual system operation. Equivalent loads L1 and L2 at the local bus and L3 and L4 at the GPIC bus are modeled as

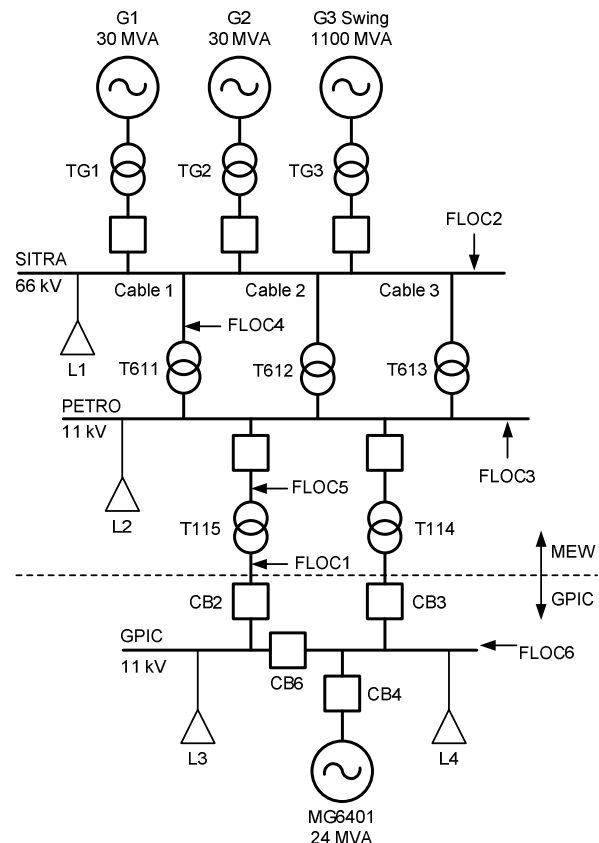lumped static and induction motor loads. Large motors at the GPIC bus are also modeled independently.

Fig. 9.   Simplified model of GPIC and MEW

66 kV Cables 1, 2, and 3 connect the Sitra 66 kV bus and Petro 11 kV bus via 66/11 kV transformers T611, T612, and T613, respectively. The length of these cables is more than 9 kilometers, making them a significant source of reactive power during normal operating conditions. Transformers T611, T612, and T613 feed the Petro 11 kV bus, which connects the GPIC substation via 11/11 kV T114 and T115 transformers.

The GPIC CGT governor operates in droop mode when the GPIC system is connected to the MEW grid. The governor changes to isochronous mode as soon as it is islanded from the MEW system. Governor mode control was accurately modeled and validated using simulations.

The CGT governor and exciter modeling were the most difficult (and critical) parts of system modeling and validation. To get governor and exciter tuning parameters to represent the GPIC system, a 50 percent step in load was utilized to evaluate the GPIC system response, including the exciter and governor. Fig. 10 shows the GPIC generator response for the step load, which was held on for 75 cycles. Final governor and exciter model performance was fine-tuned to match actual data gathered from several field step-load tests. The procedure used for data gathering and model assessment is outlined in a recent technical paper [8].
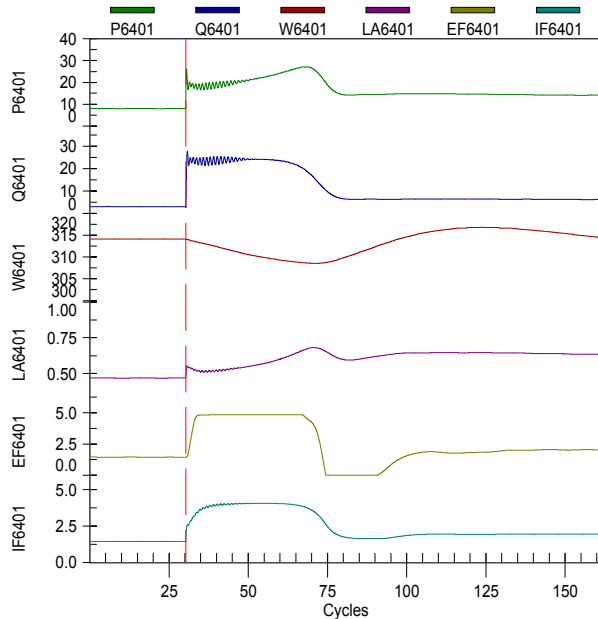

Fig. 10.   50 percent step load on the MG6401 generator

The CGT and associated mechanical fuel valves were modeled in a simplified manner. All major mechanical assemblies were modeled. Performance was validated against data from field step-load tests.

A full synchronous machine model (based on Park's equations) was used for the generator attached to the CGT. Parameters were from nameplate and manufacturer test data. Performance was validated against transient and subtransient short-circuit data from the machine manufacturer.

Transformers T114 and T115 were modeled as on-load tap changers to study the circulating current and reactive power. These transformers were modeled an equivalent of 16 taps with a total voltage variation of ±10 percent. The tap position of the transformers was changed to study the circulating current between the two tie transformers and select the settings for circulating currents; the automatic load tap changer algorithm was also included in the dynamic study.

The completed system model was validated using the following means:

- Governor and exciter model responses were compared against step-test data gathered from the field.
- Load flow data from the live facility were compared against steady-state conditions on the simulation.
- Short-circuit studies from several prior studies were compared against short-circuit conditions simulated in the live simulation system.
- Motor starting data from several prior studies were compared to simulated results.

B. Validation of ADS Operation

After model validation, the ADS was connected to the live, real-time modeling system. The ADS panel was tested by connection to the system modeling hardware, as shown in Fig. 11. The system operation was tested for faults at all locations, including tie lines close to the GPIC and MEW systems and for generation or load loss at GPIC/MEW, including possible system contingencies.
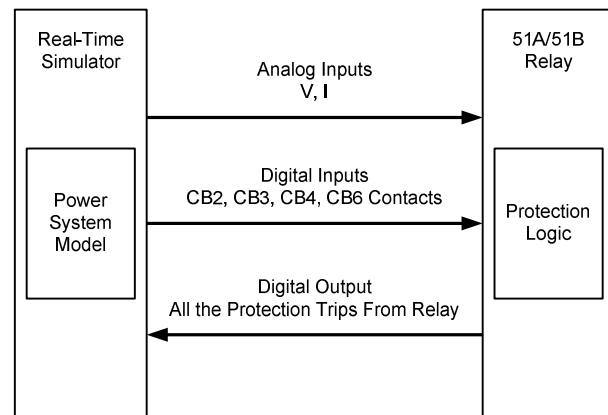

Fig. 11.   ADS connected to real-time simulation for validation testing

Motor starts and trips at GPIC were simulated. Additional analysis was performed to determine the sensitivity of reverse power to avoid the decoupling system operation on reverse power for a major motor bus fault in the GPIC system.

C. Explanation of Settings

Undervoltage, underfrequency, and overfrequency were selected based on the history of normal operation for the MEW and GPIC systems. The selected settings were also coordinated with the existing settings of protective relays on the GPIC system.

Circulating current thresholds were selected based on an acceptable transformer tap difference between the two main incomer transformers, T114 and T115.

Phase angle separation was selected such that if the voltage angle between GPIC and MEW was greater than 10 degrees, tripping was initiated. Angle selection was based on the

normal operating point of 1 MW and the transformer impedance.

Normal, minimum, and maximum power flow and various possible system contingency conditions were tested using live simulation to ensure the system did not become islanded for normal system operation. A pickup time delay of 10 cycles was selected to ensure that the ADS allows primary protection systems in MEW and GPIC time to operate.

D. Live Modeling Results

This section is a shortened summary of the ADS reaction to several fault types. These data were gathered with the final settings shown in Table I. All data for this section were collected from the ADS while connected to the real-time modeling system.

Fig. 12 indicates the line-to-line fault at FLOC1 (Fault Location 1). All the fault locations that were analyzed for this study are shown in Fig. 9. The fault is an A-C (R-B) phase fault. The results indicate that phase angle and undervoltage (UV) operate and correctly island GPIC.
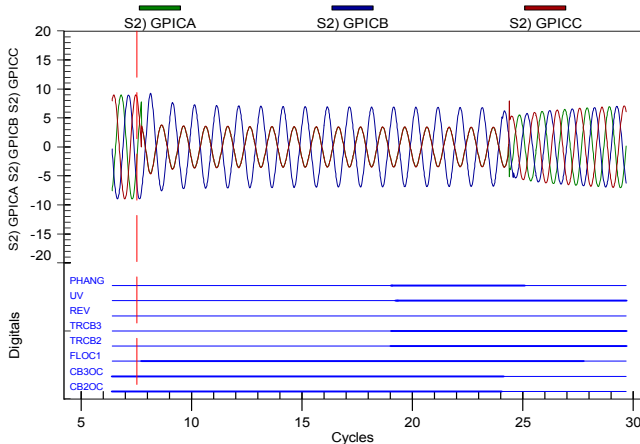

Fig. 12. FLOC1, line-to-line fault – PHANG (phase angle) and UV trip

This testing shows the ADS set points to be insensitive to the tripping of one 30 MW unit at the local MEW generation station. The pickup set points for all elements were selected for this criterion, because stability studies indicated that the GPIC system will survive this outage. The ADS will island GPIC for a loss of more than one unit at Sitra in the MEW system.

From the results of this study, it was concluded that the decoupling system will operate in less than 0.5 seconds for all fault conditions.

Note that primary protection should operate before the ADS for most severe faults. However, because the protection of the MEW is outside the control of GPIC, the ADS acts as a GPIC-owned backup method of preventing cascading outages, should primary protection fail.

VIII. GPIC DECOUPLING PANEL OPERATION DETAILS

The ADS has recorded and operated for several events since its installation in November 2007. The following is a summary of an event that occurred on March 5, 2008. On that day, the decoupling panel tripped the breakers (CB2 and CB3)

because of reverse power element operation. GPIC was islanded from an electrical disturbance on the MEW side.

Fig. 13 shows the waveforms and relay reverse power element operations for this event, where:

PSV01 represents reverse power CB2 start.

PSV02 is reverse power CB3 start.

PSV03 is reverse power CB2 trip after 15 cycles.

PSV04 is reverse power CB3 trip after 15 cycles.
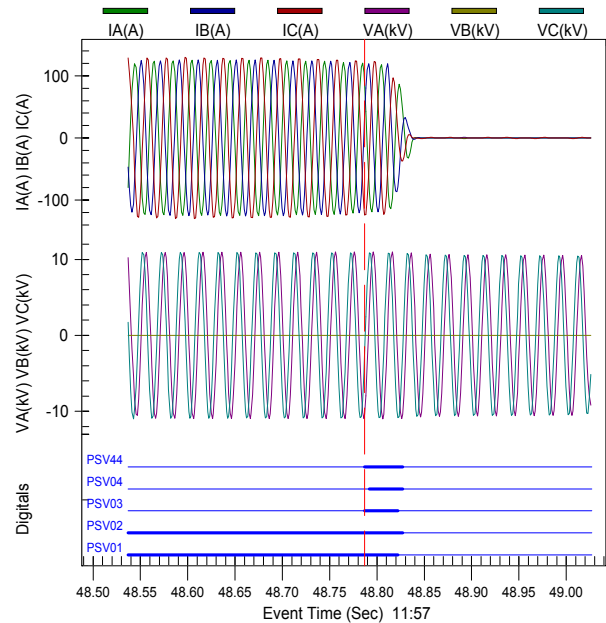
PSV44 is reverse power trip.

Fig. 13. March 5, 2008 event report

Fig. 14 shows the phasor diagrams of the voltages and currents during the events.
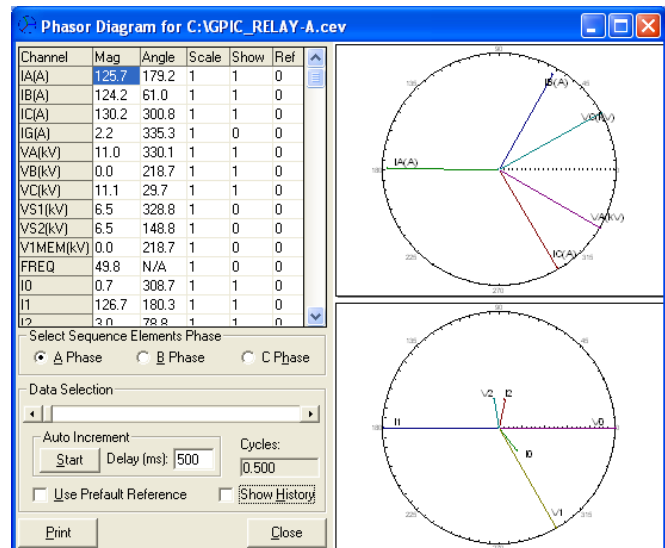

Fig. 14. Phasor diagrams showing voltages and currents

The event report details indicate the reverse power alarm and trip operations for Breakers CB2 and CB3. The reverse power alarms operated at 11:57:48:732 and 734. The reverse power trip for CB2 and CB3 operated at 11:57:48:787, and

relay LO asserted at the same time. Because the disturbance was in the external system, the ADS recorded reverse power flow on the tie lines. Because the alarm was selected at a lower setting, the reverse power alarm operated first, and then the reverse power trip operated. The ADS successfully operated and islanded the GPIC system for an external disturbance.

IX. CONCLUSION

This decoupling panel for GPIC was supplied in 2007, has operated several times, and has islanded the GPIC system correctly. The ADS has never misoperated, nor has any equipment failed. These successes are attributed to the use of ultra-reliable protection components, extensive modeling, and validation of system performance prior to system installation.

ADS testing provided critical insight into the system operation and set-point selection. Live system testing allowed engineers an experimental test bed to greatly refine set-point selections.

In 2010, the logic was modified, and the synchrophasor element was enabled to detect df/dt and monitor the utility network voltage waveform.

X. APPENDIX: TERMINOLOGY DEFINITIONS FOR FIG. 6

ALT	Automation freeform latch bits
AMV	Protection control equation math variables
AST	Automation freeform sequencing timers
ASV	Automation control equation variables
PCT	Protection freeform conditioning timers
PLT	Protection freeform latch bits
PMV	Protection control equation math variables
PST	Protection freeform sequencing timers
PSV	Protection control equation variables

XI. ACKNOWLEDGMENT

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XIII. BIOGRAPHIES

Ameer Al-Mulla is an electrical maintenance superintendent at Gulf Petrochemical Industries Company (GPIC) in Bahrain. He obtained his degree in electrical and electronics engineering from Sunderland Polytechnic, U.K., in 1987. He is a certified maintenance and reliability professional (SMRP, USA). Before joining GPIC in June 2001, Ameer had 19 years of experience in electrical maintenance and 7 years as head of the planning section at a power generation and water desalination facility.

Kamal Garg is a project engineer in the engineering services division of Schweitzer Engineering Laboratories, Inc. He received a master's degree in electrical engineering from Florida International, Miami, and IIT Roorkee, India, and a bachelor's degree in electrical engineering from KNIT, India. Kamal has experience in protection system design, system planning, substation design, operation, testing, and maintenance.

Scott Manson is a supervising engineer in the engineering services division of Schweitzer Engineering Laboratories, Inc. (SEL). He received a master's degree in electrical engineering from the University of Wisconsin–Madison and a bachelor's degree in electrical engineering from Washington State University. Scott worked at 3M Corporation as a control system engineer for six years prior to joining SEL in 2002. Scott has experience in designing and implementing control systems for electrical utility customers, high-speed web lines, multi-axis motion control systems, and precision machine tools.

Ahmed El-Hamaky is an application engineer with Schweitzer Engineering Laboratories, Inc. He received a bachelor's degree in electrical engineering from Cairo University, Egypt. Ahmed has extensive experience in the application of protection schemes for different voltage level substations, fault analysis, testing, and troubleshooting of protective relays.