Case Study: A Dual-Primary Redundant Automatic Decoupling System for a Critical Petrochemical Process

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CASE STUDY: A DUAL-PRIMARY REDUNDANT AUTOMATIC DECOUPLING SYSTEM FOR A CRITICAL PETROCHEMICAL PROCESS

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Abstract—Gulf Petrochemical Industries Company (GPIC), located in Sitra, Kingdom of Bahrain, operates a petrochemical complex consisting of a 1200 MTPD (metric tons per day) ammonia plant, a 1200 MTPD methanol plant, and a 1700 MTPD urea plant.

GPIC selected a new dual-primary redundant automatic decoupling system (ADS) to island their system for external system disturbances. The as-built ADS was validated against a real-time digital simulation system. The real-time system modeling made it possible to validate the decoupling system operation for various system disturbances and select the set points accordingly.

Since installation, the new ADS has operated correctly several times to island the GPIC system.

Index Terms—decoupling, separation, automatic islanding system, protection, blackout remediation, system stability, dual-primary protection, phase angle, DFDT, reverse power, circulating current, reverse MVAR, synchrophasor.

I. INTRODUCTION

Due to 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.

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 MEW system disturbances.

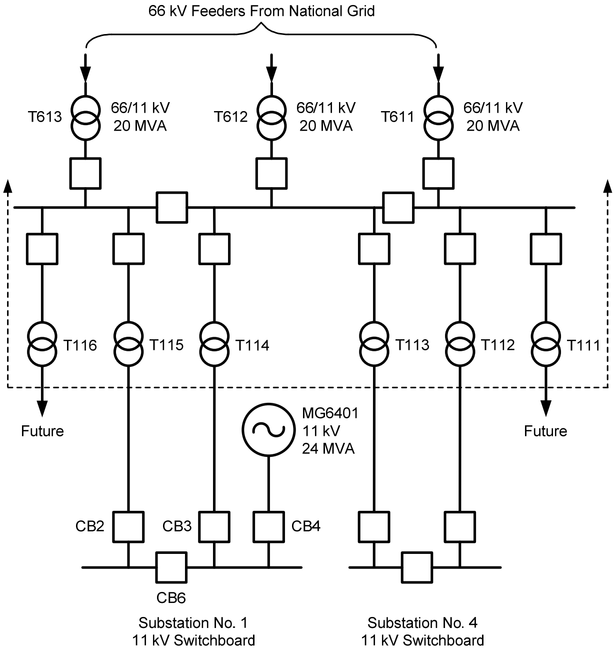


Fig. 1 Feeding Arrangement to Petrochemical Complex

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 [1][2][3].

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:

- Misoperation
- 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 misoperate at least once. In this instance, the old decoupling system failed to operate during a major voltage depression (brownout) in MEW, nearly resulting in a complete process outage at GPIC.

The old decoupling device did not provide any system operation details, event report analysis data, system alarms, or SOE (sequence of events) reports. It also did not communicate to SCADA (supervisory control and data acquisition) for information or control. The old system was not capable of providing new protection functions, such as phase angle and rate of change of frequency (DFDT). In the absence of event diagnostic functions, it was difficult to analyze any disturbances or system operations.

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 SOE monitoring, and remote SCADA monitoring and control.

IV. HISTORY OF SYSTEM DISTURBANCES

System disturbances are common occurrences on the MEW network. The GPIC electrical system can become unstable after some disturbances. It has a history of instability due to one or more of the following system disturbances:

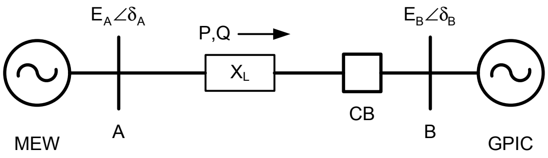
- System fault
- Disconnect of any large load
- Trip of any large MEW generator
- Erroneous system operation or failure of control system
- Lack of reactive power (low MEW voltage)
- Lack of active power (low MEW frequency)

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 (OOS) 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 as 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). Fig. 3 shows the power transfer at different machine internal angles.



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

$$Q = \frac{E_B}{X_L} \bullet \left[E_A \bullet \cos(\delta_A - \delta_B) - E_B\right]$$

Fig. 2 Simplified Two-Machine Model

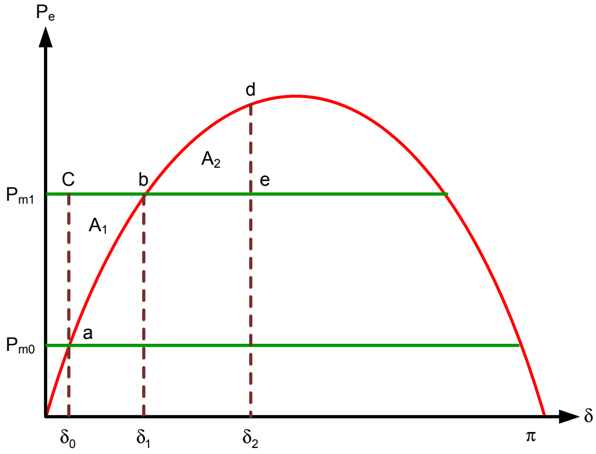


Fig. 3 Maximum Power and Equal Area

The system may settle at a different stable point if the system configuration changes due to 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

Decoupling relays 51A and 51B (microprocessor-based bay control relays) are identical in functionality [5]. Each relay simultaneously performs decoupling protection for both breakers; therefore, this is considered a “dual-primary” protection scheme.

A. Communications Architecture

Fig. 4 shows the communication between components in the GPIC ADS. The ADS includes an engineering station (labeled “computing platform”), which provides a graphical interface to view 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 record 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.

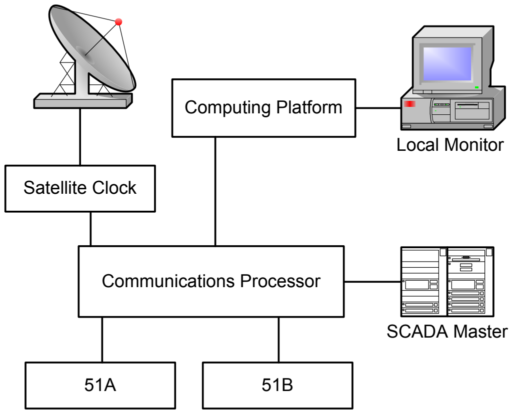


Fig. 4 Decoupling Panel Communications Diagram

B. Protection Systems

The ADS provides system islanding based on the following elements:

- Angle separation
- Reverse power
- Circulating current
- Undervoltage/overvoltage
- DFDT operation
- Underfrequency/overfrequency

Both relays independently measure these quantities for both tie lines. The settings for each protection element are listed in Table I.

TABLE I
SETTINGS FOR DECOUPLING DEVICE

	Alarm		**Trip**	
	Set Point	**Time Delay**	**Set Point**	**Time Delay**
Undervoltage	90% of nominal	10 cycles	80% of nominal	10 cycles
Underfrequency	49.5 Hz	10 cycles	49 Hz	10 cycles
Reverse power (both CB2 and CB3 closed)	80% of trip	15 cycles	–1.0 MW	15 cycles
Reverse power (when only one of the breakers is in service)	80% of trip	15 cycles	–1.75 MW	15 cycles
Circulating current	80% of trip	10 seconds	5 MVAR	10 seconds
Angle separation: A-phase C-phase	65° 5°	10 cycles 10 cycles	70° 10°	10 cycles 10 cycles
Overfrequency	50.5 Hz	10 cycles	51.0 Hz	10 cycles
DFDT	1.0 Hz/s	No delay	1.5 Hz/s	No delay

As shown in Fig. 5, each relay has potential transformer (PT) connections on both the MEW and GPIC sides of T114 and T115. This is for phase angle measurement of the synchrophasor across the transformer. A two-phase, open-delta PT is available from the GPIC side, and a three-phase, wye PT voltage is available from the MEW side. The phase angle set point is selected to detect the phase shift between GPIC and MEW for both A- and C-phase. Phase shift due to wye-delta transformers, PT connections, and load-flow angles is also considered.

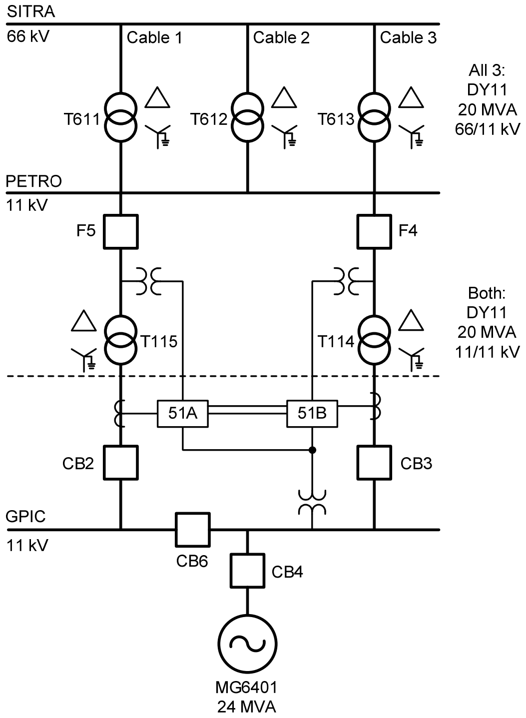


Fig. 5 New ADS for GPIC

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 internal to 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 will most commonly occur during misoperations and failures of the load tap changer.

Tripping from the decoupling device is disabled when GPIC generation is out of service. The tripping is also wired in the block close circuit of the GPIC Breakers CB2 and CB3.

DFDT protection logic is set up with a combination of digital filtering and rated detection logic. No time delay is selected for the DFDT settings; rather, the filtering is adjusted to avoid spurious trips. DFDT settings are selected to avoid system operations during system transients.

System trip and block close outputs from the relays are latched until manually reset by an operator, making the ADS act as a lockout relay. No auxiliary interposing or lockout relays were used.

Overfrequency protection is employed to decouple from MEW for a major loss of load on MEW.

DFDT detection was studied in detail for various system disturbances on the real-time system simulation. Initial DFDT thresholds and filter time constants were selected based on these studies.

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].

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

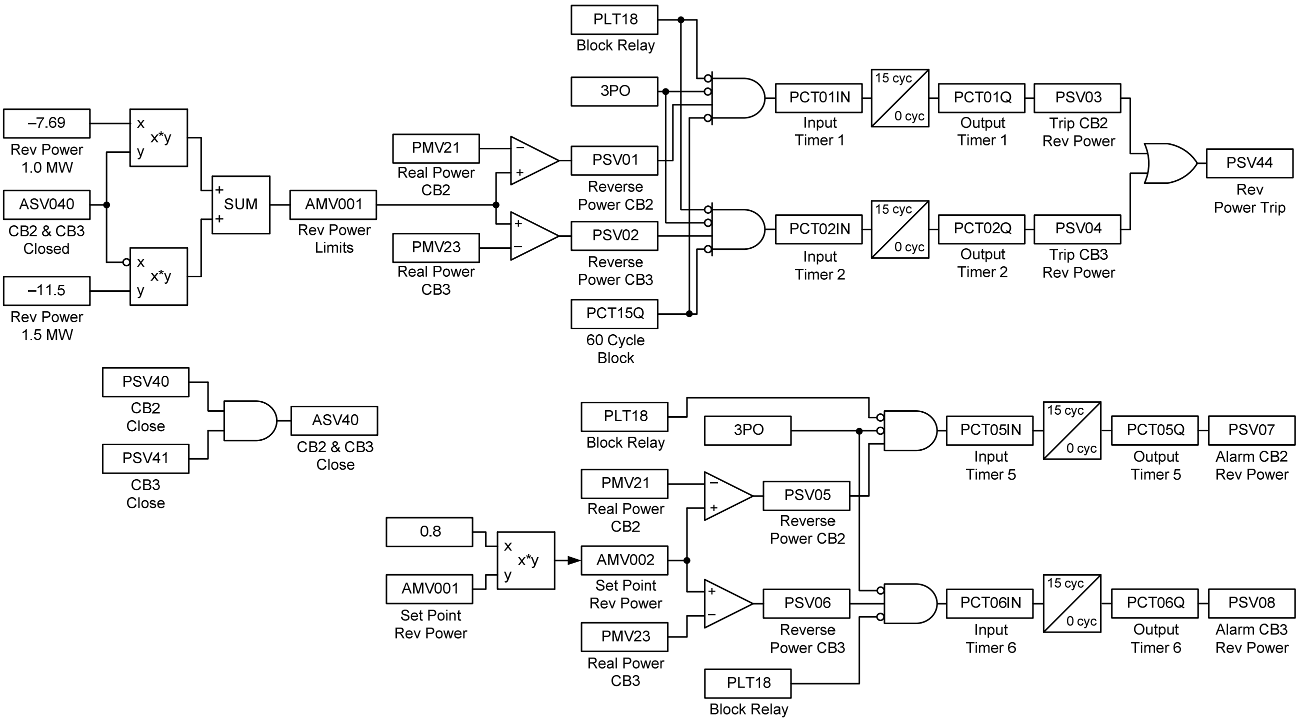


Fig. 6 Reverse Power Logic

Every trip event is annunciated onto front-panel indicator LEDs (light-emitting diodes) on both 51A and 51B, allowing for immediate recognition of the trigger for a decoupling event. Directly adjacent to each trip LED is an alarm LED. All alarms and trips are captured to SOE data points for long-term storage on the computing platform. Fig. 7 and Fig. 8 show the ADS protective relay front-panel LEDs and pushbuttons. Fig. 7 indicates the reverse power trip and both CB2 and CB3 breakers open. Fig. 8 indicates the circulating current protection operated for CB3 and Breaker CB3 is open.

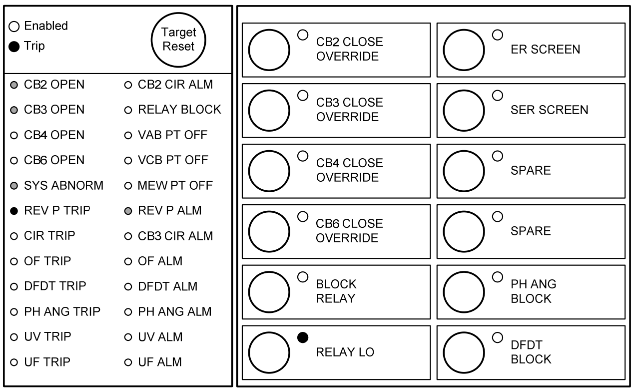


Fig. 7 Reverse Power Alarm and CB2 and CB3 Trip

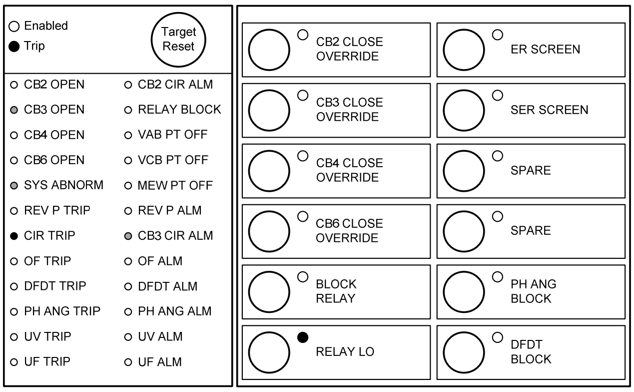


Fig. 8 CB3 Circulating Alarm and CB3 Trip

Alarm logic is identical to tripping logic but with lowered pickup set points. Please refer to Table I for the alarm and tripping set points. The alarm indications provide a valuable long-term benefit to fine-tuning the sensitivity of the trip set points. The alarms indicate how close and how frequently the ADS comes to actually tripping. Since installation, the historical monitoring tools (SOE, DFR, and LEDs) have been used to improve the trip setting pickups, further improving system sensitivity and selectivity.

Illuminated pushbuttons on 51A and 51B supply further functionality, including the following:

- Trip lockouts are indicated and reset by LEDs and pushbuttons on the 51A and 51B front panels.
- DFDT and phase angle protection trip elements are blocked using pushbuttons. Decoupling device relays communicate via a peer-to-peer communications channel to keep both elements in both relays identically blocked. This allows GPIC to block the functions newly introduced to the system.
- Breaker 52A status signals are bypassed by pushbuttons. When bypassed, the relay will assume the associated breaker is closed for internal logic. This functionality was added to prevent the decoupling action from being disabled by a failed breaker status indication (broken wiring to the breaker).
- SOE and event report (ER) screens can be accessed directly using the pushbuttons to quickly understand the relay operation. A {BLOCK RELAY} pushbutton is also provided to block the tripping from the ADS. A {RELAY LO} pushbutton is provided to reset the relay. Alarms are indicated with yellow, and trips and critical operations are indicated with red LEDs next to the pushbuttons.

The front panel of each 51A and 51B protective relay also includes a summarized graphical display (one-line bay diagram) of the breaker statuses and power flows. Fig. 9 shows the interface displayed on the bay control. In the figure below, TR1, TR2, and A1 through A4 indicate the T114 and T115 transformer flows in MW and MVAR. A5 and A6 indicate the line voltage of the GPIC bus. BK1 through BK3 also provide the status of GPIC tie breakers CB2 and CB3 and GPIC generator MG6401 Breaker CB4. From the one-line bay diagram, it is possible to get an overview of the GPIC Substation No. 1 operating conditions.

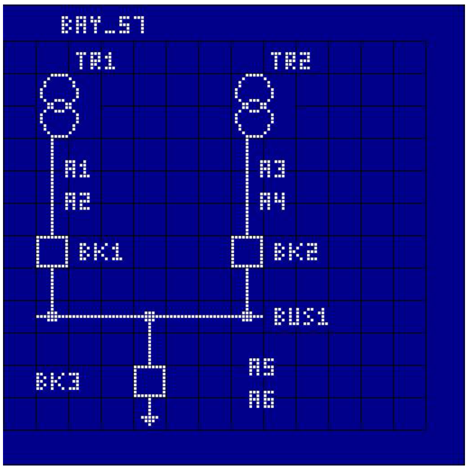


Fig. 9 Decoupling System Bay Diagram

The ADS is blocked for 1 second after any of the breakers (CB2, CB3, CB4, or CB6) operate. This option was provided to avoid tripping the decoupling device due to transients.

VI. SYSTEM MODELING AND VALIDATION

The scope of work discussed in this section includes:

- Model development
- Model validation
- ADS operation validation

A. Model Development

A detailed system model was prepared for the GPIC and MEW system based on the system data and nameplate information collected from a site visit. A summary of the dynamic simulation model for the ADS is shown in Fig. 5.

Fig. 10 illustrates the GPIC and MEW system model built into the real-time digital simulation system. Two units, G1 and G2, at MEW 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, suitable governor and exciter response, transient and subtransient time constants, and correct short-circuit current capability. Loads L1 and L2 at the Sitra and Petro buses and L3 and L4 at the GPIC bus are equivalent loads that represent several static and induction motor loads. Large motors at the GPIC bus are also modeled independently.

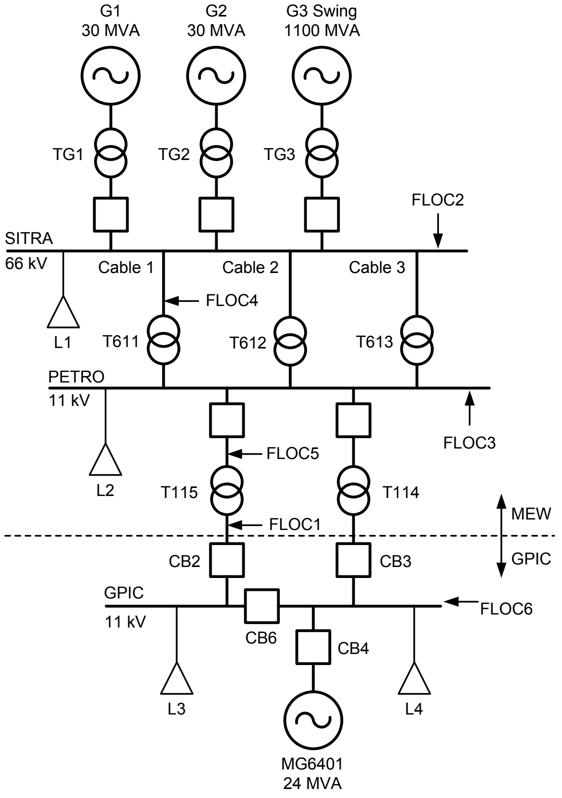


Fig. 10 Simplified Model of GPIC and MEW

66 kV Cables 1, 2, and 3 connect the Sitra 66 kV bus and Petro 11 kV bus via 66 kV/11 kV transformers T611, T612, and T613, respectively. The length of these cables is more than 9 km, 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 the 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 the system modeling and validation. To validate the CGT governor and exciter models, a 50 percent step in load was added to the GPIC system. Fig. 11 shows the GPIC generator response for the step load (that was held on for 75 cycles). Final governor and exciter performance was fine-tuned to match actual data gathered from several field step-load tests.

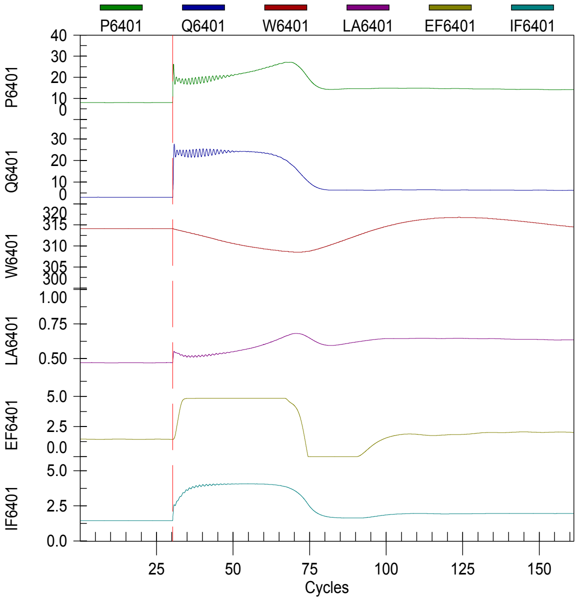


Fig. 11 50 Percent Step Load on the MG6401 Generator

The CGT and associated mechanical fuel valves were modeled in a simplified manner. All major mechanical assemblies were modeled. Performance was validated against engineering experience with such systems.

A full synchronous machine model (based on Park's equations) was used for the generator attached to the CGT. The parameters were from nameplate and manufacturer test data. The 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 (OLTC) to study the circulating current and reactive power. These transformers were modeled 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 completed system model was verified for correctness (validated) using the following means:

- 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. 12.

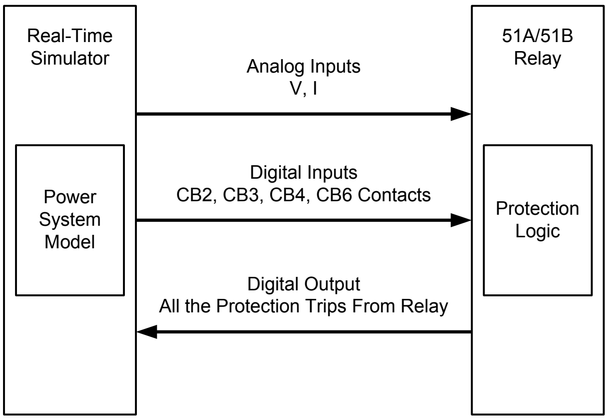


Fig. 12 ADS Connected to Real-Time Simulation for Validation Testing

The real-time simulation setup shown in Fig. 12 was used to determine ADS performance for several faults and contingencies. Faults at the tie lines to MEW, bushing faults, cable faults, and faults at GPIC were modeled. Contingencies such as a sudden loss of generation or load were also tested.

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.

Undervoltage, underfrequency, and overfrequency were selected based on the history of normal operations 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 interconnection 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.

C. 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 it was connected to the real-time modeling system.

Fig. 13 indicates the L-L (line-to-line) fault at FLOC1 (Fault Location 1). The fault is a R-B-phase (red and blue phases, equivalent to A- and C-phase in North America) fault. The results indicate that phase angle and UV (undervoltage) operate and correctly island GPIC.

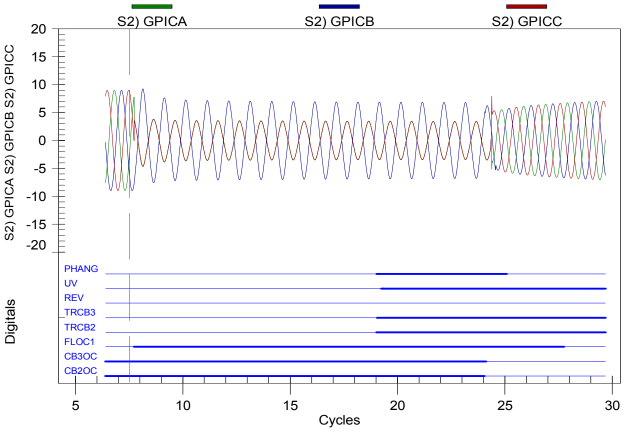


Fig. 13 FLOC1, L-L Fault – PHANG (Phase Angle) and UV Trip

This testing shows the ADS set points to be insensitive to the tripping of one 30 MW unit at the MEW Sitra station. The pickup set points for all elements were selected for this criterion. This was 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.

From the results of this study, it can be concluded that the decoupling system will operate in less than 0.5 seconds for all fault conditions and MEW outages except B-phase faults. The voltage from the B-phase is not available because this is an open-delta PT connection.

Note that primary protection should operate before the ADS does for most severe faults. However, since 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.

VII. 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 the event that occurred March 5, 2008. On that day, the decoupling panel tripped the breakers (CB2 and CB3) due to reverse power element operation and islanded GPIC from an electrical disturbance on the MEW side.

Fig. 14 shows the waveforms and relay reverse power element operations for this event, where:

PSV01 = reverse power CB2 start.
PSV02 = reverse power CB3 start.
PSV03 = reverse power CB2 trip after 15 cycles.
PSV04 = reverse power CB3 trip after 15 cycles.
PSV44 = reverse power trip.

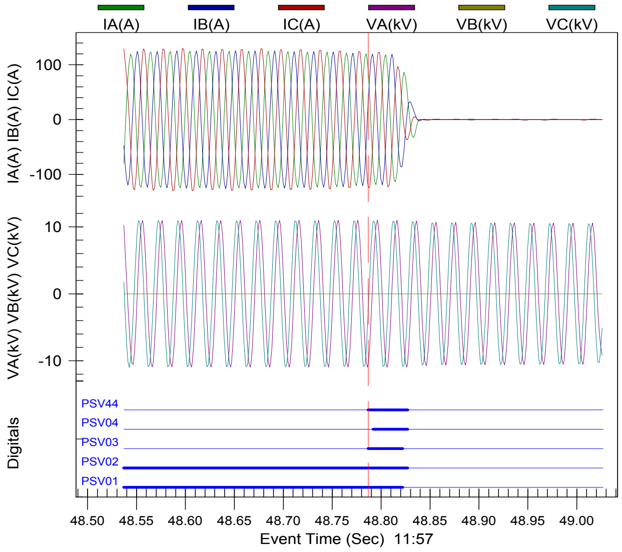
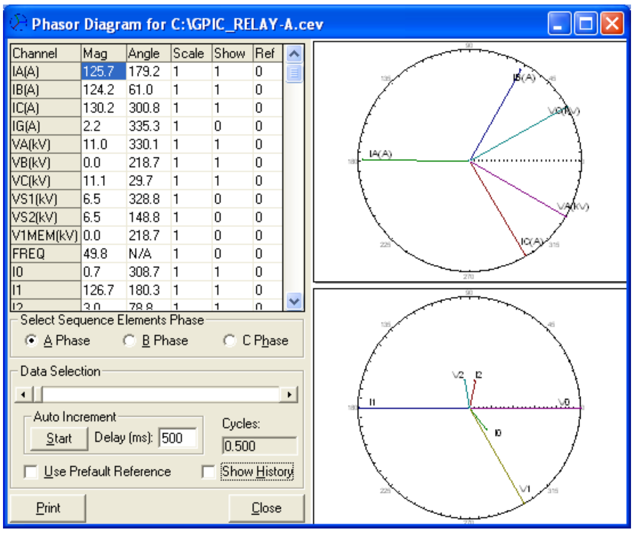


Fig. 14 Event Report Dated 5th of March 2008

Fig. 15 shows the phasor diagrams of the voltages and currents during the events.

The event report details indicate the reverse power alarm and trip operation for both 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. Since 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 system successfully operated and islanded the GPIC system for an external disturbance.



Channel	Mag	Angle	Scale	Show	Ref
IA(A)	125.7	179.2	1	1	0
IB(A)	124.2	61.0	1	1	0
IC(A)	130.2	300.8	1	1	0
IG(A)	2.2	335.3	1	0	0
VA(kV)	11.0	330.1	1	1	0
VB(kV)	0.0	218.7	1	1	0
VC(kV)	11.1	29.7	1	1	0
VS1(kV)	6.5	328.8	1	0	0
VS2(kV)	6.5	148.8	1	0	0
V1MEM(kV)	0.0	218.7	1	0	0
FREQ	49.8	N/A	1	0	0
I0	0.7	308.7	1	1	0
I1	126.7	180.3	1	1	0
I2	3.0	78.8	1	1	0

Select Sequence Elements Phase
● A Phase ○ B Phase ○ C Phase

Data Selection

Auto Increment
Start Delay (ms): 500
Cycles: 0.500

☐ Use Prefault Reference ☐ Show History

Fig. 15 Phasor Diagrams Showing the Voltages and Currents During the Event

VIII. CONCLUSION

The decoupling panel for GPIC was supplied in 2007 and has operated several times and 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 the system installation.

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

IX. ACKNOWLEDGEMENT

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XI. VITAE

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