Saudi Aramco Experience – Islanding Scheme for Manifa Central Processing Facility

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Abstract—Manifa Central Processing Facility (CPF), the fifth largest oil field in the world, is connected by 25 manmade islands and 20 kilometers of causeways. The current production capacity of heavy crude oil at the CPF is 500,000 barrels per day (bpd). The full production capacity of the plant is 900,000 bpd, which the facility will meet in 2014. The power plant generation includes two combustion gas turbine (CGT) generators and two heat recovery steam generators (HRSGs) providing steam to two steam turbine generators (STGs), with a total generation capacity of about 500 MW.

Two tie lines at 115 kV connect the Manifa CPF to the external utility system. A power management system controls the Manifa CPF frequency once the Manifa CPF islands from the external grid. Some of the severe external disturbances require Manifa islanding operation in less than 15 cycles to maintain system stability. This very critical CPF requires the ability to quickly identify an islanding condition correctly. This paper discusses the islanding scheme design details for local and remote signals. For significant power exchange with an external grid, local measurement-based islanding can correctly and quickly identify the islanding condition.

Index Terms—closed-loop testing, decoupling, DFDT, fast DFDT, islanding, stability, synchrophasors, wide-area monitoring.

I. INTRODUCTION

Because of crucial safety consequences related to the uncontrolled shutdown of Manifa Central Processing Facility (CPF), a gas and crude oil facility, the critical load is fed by a redundant power scheme. The Manifa CPF uses a dual 115 kV feed from the national grid owned by Saudi Electricity Company (SEC) as well as two combustion gas turbine (CGT) generators that are 154 MW each and two steam turbine generators (STGs) that are 70 MW and 40 MW. Either the feeders or the generators are capable of supplying the entire process electrical load (see Fig. 1 in the next section). The entire Manifa CPF relies on the power generated by these four generators. Excess power is exported to the SEC national grid. The electrical system is thus designed so that the loss of either the generators or the SEC network is acceptable, but a loss of both sources shuts down the entire Manifa CPF. Losing a CGT generator means also losing steam from a heat recovery steam generator (HRSG) and thus the related STG. Stable operation of the CGTs is therefore fundamental in supplying power to the site when it is in an island mode.

The CGT generators are sensitive to disturbances in the national grid. To ensure the reliability of the Manifa CPF network, an automatic decoupling system (ADS) was installed that can cater to the ever-increasing system disturbances from the rapid expansion of SEC.

The new ADS decouples (or islands) the Manifa CPF from SEC during external system disturbances. This is the first decoupling scheme introduced in a Saudi Aramco plant system. The system uses several protection elements to achieve this goal. This paper explains each of these elements and devices. The new state-of-the-art ADS also includes several engineering diagnostic features that enable both operation and maintenance personnel to quickly diagnose and understand an islanding event.

II. SYSTEM DESIGN

Fig. 1 shows a one-line diagram of the Manifa system connected to the external grid. SEC and two lines at 115 kV are connected to the Manifa CPF. For simplification, SEC is shown as a radial bus, but in reality, it is a breaker-and-a-half protection scheme at the SEC 380 kV end. At the Manifa end, two decoupling devices, Relay A and Relay B, are installed for the islanding scheme. Current transformers (CTs) and potential transformers (PTs) are tapped from the existing line protection relays. Relay A works as islanding for Line A and Relay B for Line B. Both relays are connected to the Global Positioning System (GPS) clock signal because many protection elements such as rate of change of frequency (DFDT) and fast DFDT use synchrophasor quantities. The present scheme does not include wide-area monitoring and control. However, the present scheme is scalable and has already been vetted for a wide-area monitoring and control scheme using synchrophasors [1]. Front-panel monitoring is also available for system diagnostics and protection element operation. All the critical information is logged in the local relays and at the central location for monitoring. Fail-safe contacts from decoupling devices Relay A and Relay B are wired for remote monitoring and failure indication.

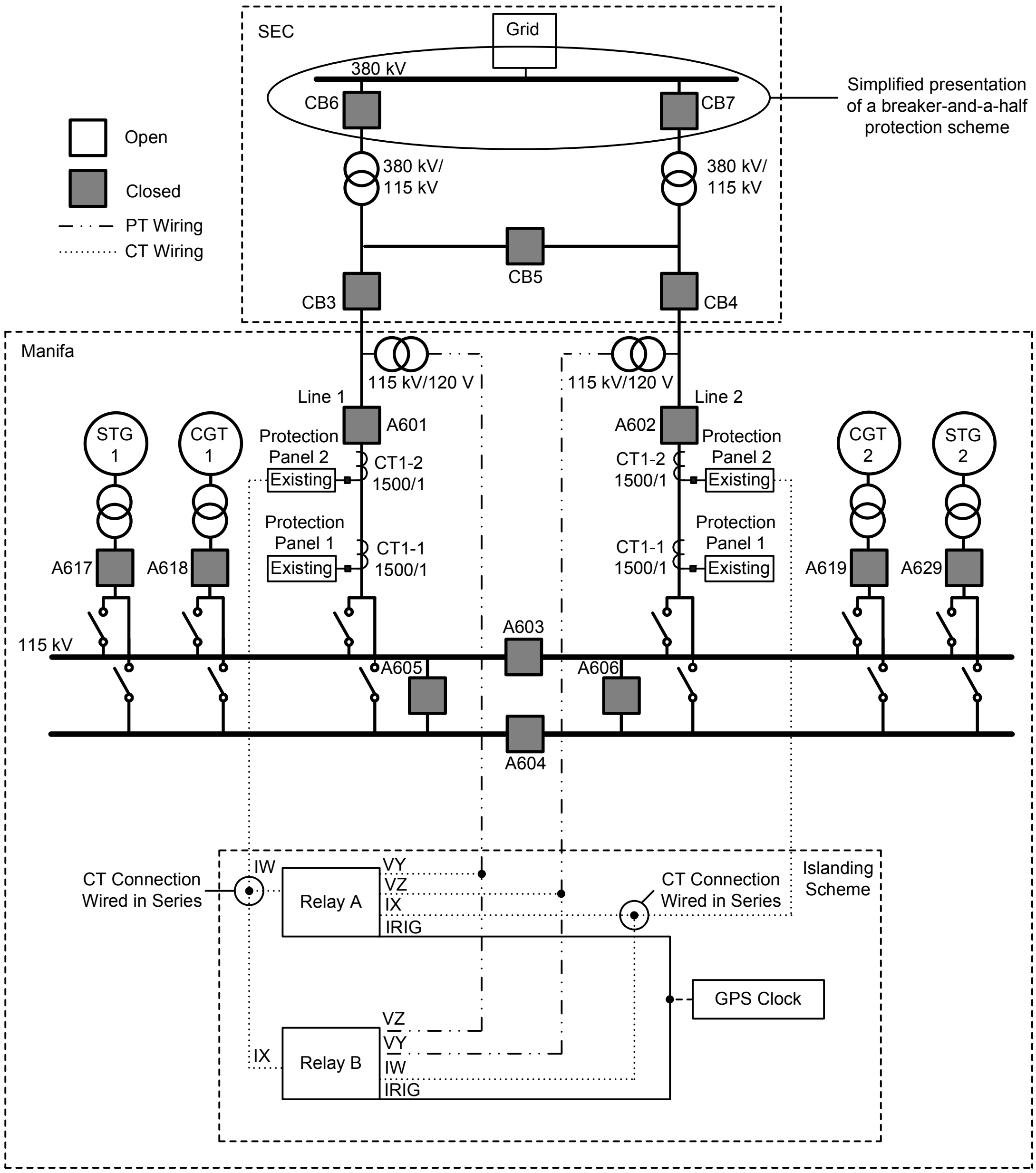

Fig. 1. Manifa System One-Line Diagram

III. SYNCHROPHASORS

A. *Synchrophasor Message Format*

Synchrophasors are widely used today to monitor the state of the power system [2] [3] [4]. In the near future, it is anticipated that synchrophasors will be used for various control applications if wide-area synchronized system information is available. IEEE C37.118-2005 and IEEE C37.118-2011 [5] define synchronized phasor measurements as well as the message format for communicating these data in a real-time system. While most people think of these standards with regard to sending time-coherent voltage and current phasors, IEEE C37.118 messages can be used to provide much more information (such as additional analog data, digital status information, and control signals) as part of the synchrophasor packet.

A phasor is a voltage or current of the ac system and can be represented in a steady state by perfect sinusoidal functions. Fig. 2 shows an example of a sinusoidal voltage function called v(t), with a period of *T* seconds.

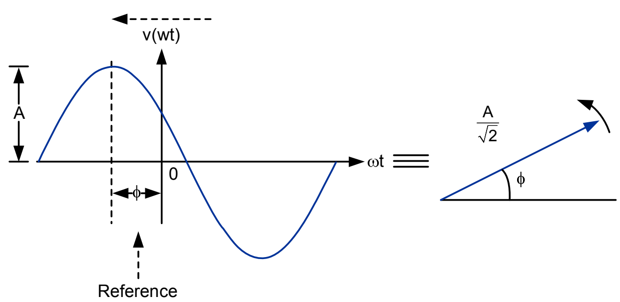

Fig. 2. Sinusoidal Voltage Time Waveform and Phasor Presentation

B. Wide-Area Monitoring and Applications

Synchronized measurements of voltage phasors, current phasors, and frequency are key to power system analysis. The Coordinated Universal Time (UTC) reference and the synchronized voltage signal provide a snapshot across the power system, as illustrated in Fig. 3.

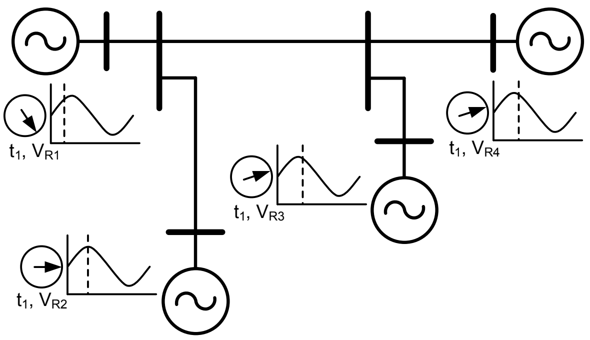

Fig. 3. Wide-Area Synchronized System

Some synchrophasor applications include the following:

- State measurement
- Real-time monitoring (V, I, P, Q, and f)
- Power system model validation
- Situational awareness
- System restoration
- Stability analysis
- Event analysis
- Wide-area monitoring and control

Traditional information management systems and protocols (e.g., DNP3, Modbus®, and OPC) that are used to communicate information back to a central location only send magnitude measurements. These systems update information every few seconds to every few minutes. Additionally, the data are not time-coherent or time-stamped, making it difficult to accurately assess system conditions. Using synchronized measurements helps overcome these shortcomings and provides many additional benefits. One possible application is to use phasor measurement unit (PMU) synchrophasor measurements for dynamic model verification. Many utilities archive years of PMU data, and such gathered information can be applied for wide-area system dynamic response validation and analysis. For any switching operation, a PMU-measured system response can be validated against the dynamic system model used by a planning department. PMUs can also be applied to evaluate the generator control actions and system dynamic response. This helps validate the dynamic models of exciters and governors for various system disturbances. For this application, wide-area monitoring and control application of synchrophasors can be applied to improve the decoupling scheme design.

IV. PROTECTION SCHEME DESIGN AND VALIDATION

Closed-loop digital simulations (i.e., real-time digital simulation, model validation, factory acceptance testing, and design validation) established the design parameters for this critical scheme. As part of factory acceptance testing, stability analysis determined the minimum time required for the decoupling scheme to operate and isolate for external faults [6] [7]. Even though dual-redundant line protection is available on Manifa-SEC 115 kV tie lines, Saudi Aramco decided to implement additional detection elements for external system disturbances and isolate the plant from the external grid. From various stability studies, it was determined that during certain critical operating scenarios, systems should island in less than 15 cycles. The plots in Fig. 4 and Fig. 5 show an external three-phase fault and an example where STG 1 is unstable for a 0.28-second three-phase fault but stable for a 0.27-second external three-phase fault. For the worst operating conditions, critical time was verified using closed-loop testing. The results of this study were comparable to previous stability studies done for this plant. This comparison provided additional validation of the system model for this design. The real-time digital system model was also verified for various load flow and short-circuit conditions. The dynamics of local generators and synchronous motors were verified using field data and in-service testing. In-service testing verified that dynamic system parameters can be adjusted for further improvement of system operation.

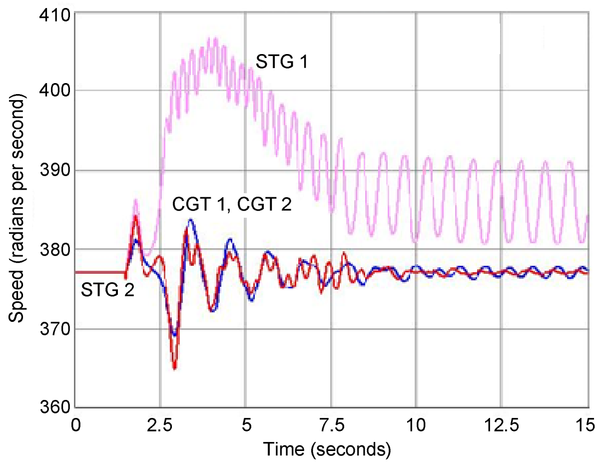

Fig. 4. Generator Speed Plot of 0.28-Second Three-Phase Fault

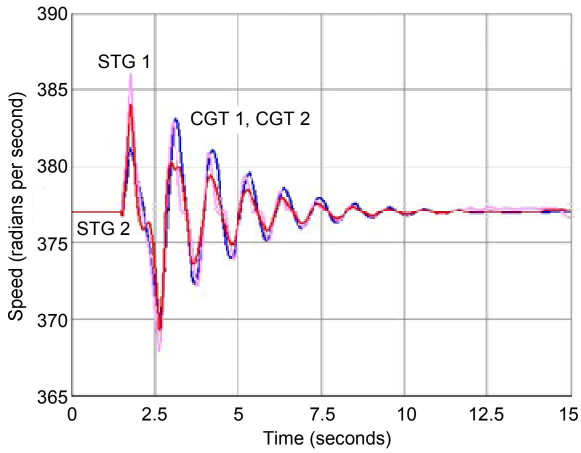

Fig. 5. Generator Speed Plot of 0.27-Second Three-Phase Fault

Because of the criticality of this decoupling scheme, multiple detection methods are enabled. Various detection elements operate in parallel, and the sensitivity of these elements was verified for various system operating conditions. Line protection provides primary protection and the decoupling system is designed to operate as secondary protection, with intentional time delay based upon system critical clearing time. Detection methods are programmed for external system disturbances only. Detection elements are limited to the SEC 115 kV bus and do not reach beyond the 115/380 kV SEC transformer. The following fault detection elements are enabled for these conditions via the decoupling system:

- Phase and ground distance
- Directional phase definite-time overcurrent
- Directional negative-sequence definite-time overcurrent (67Q1T)
- Directional residual ground definite-time overcurrent (67G1T)

The set point selection of these elements was based on the Saudi Aramco system operation philosophy, system stability requirements, and a detailed study for various system operating conditions. The primary function of these elements is to detect external system disturbances and faults and isolate the Manifa CPF to prevent a system blackout. As discussed previously, the purpose of this scheme is not to act as primary protection; therefore, adequate detection delays are programmed.

Phase overcurrent is selected above the maximum flow on the tie line connecting Manifa to SEC. Ground and negative-sequence overcurrent are selected at 25 percent of the phase overcurrent pickup. In addition, phase and ground distance elements are enabled. All of these elements are enabled in the forward direction and supervised to ensure they do not reach beyond the next substation. Voltage elements were selected based on Saudi Aramco experience with normal operating voltage conditions.

A. Local Decoupling Protection Scheme

The present decoupling scheme relies on local measurements only because remote-end system information or breaker status is not available. Decoupling schemes have been designed successfully based on local measurements only.

The following elements are enabled for this scheme based on local measurement [8] [9]:

- DFDT
- Fast DFDT (81RF)
- Underfrequency (UF) and overfrequency (OF)
- Undervoltage (UV) and overvoltage (OV)

UF and OF elements are selected to coordinate with the generator protection at 59.5 Hz and 60.5 Hz, respectively, with a 12-cycle delay. Additional UF and OF alarm elements are enabled with a 30-cycle (0.5-second) delay. UV and OV elements are selected based on the system operating conditions, with a 12-cycle delay. In this decoupling scheme, DFDT is selected at 2.5 Hz per second with a 10-cycle delay [9]. Fast DFDT of 7.5 Hz per second with –7.5 percent slope is selected. An additional fast DFDT alarm element of 5 Hz per second with –5 percent slope was also proposed and is under observation. Fig. 6 shows the fast DFDT protection operating set points and operating region. This protection was found to be sensitive for the weak system operating conditions and operates correctly and faster than DFDT. As shown in Fig. 6, this scheme adjusts the DFDT set point based on the deviation of frequency from the nominal frequency.

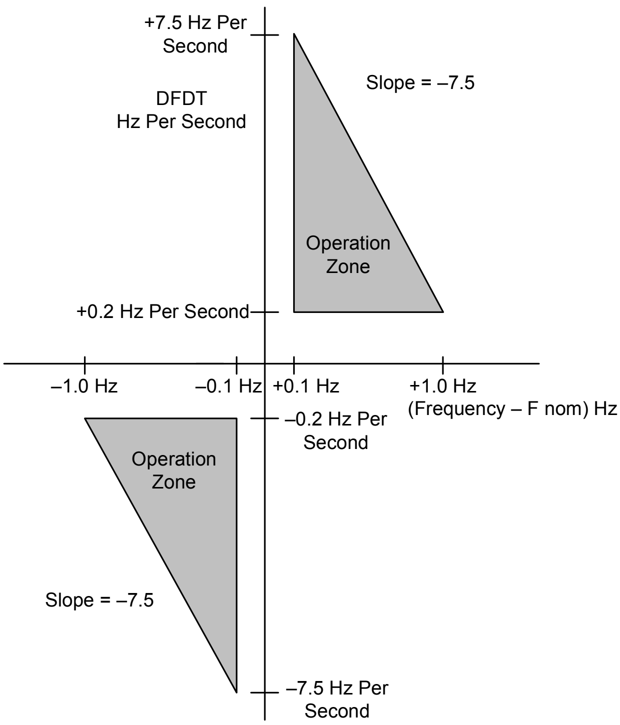

Fig. 6. Fast DFDT Logic

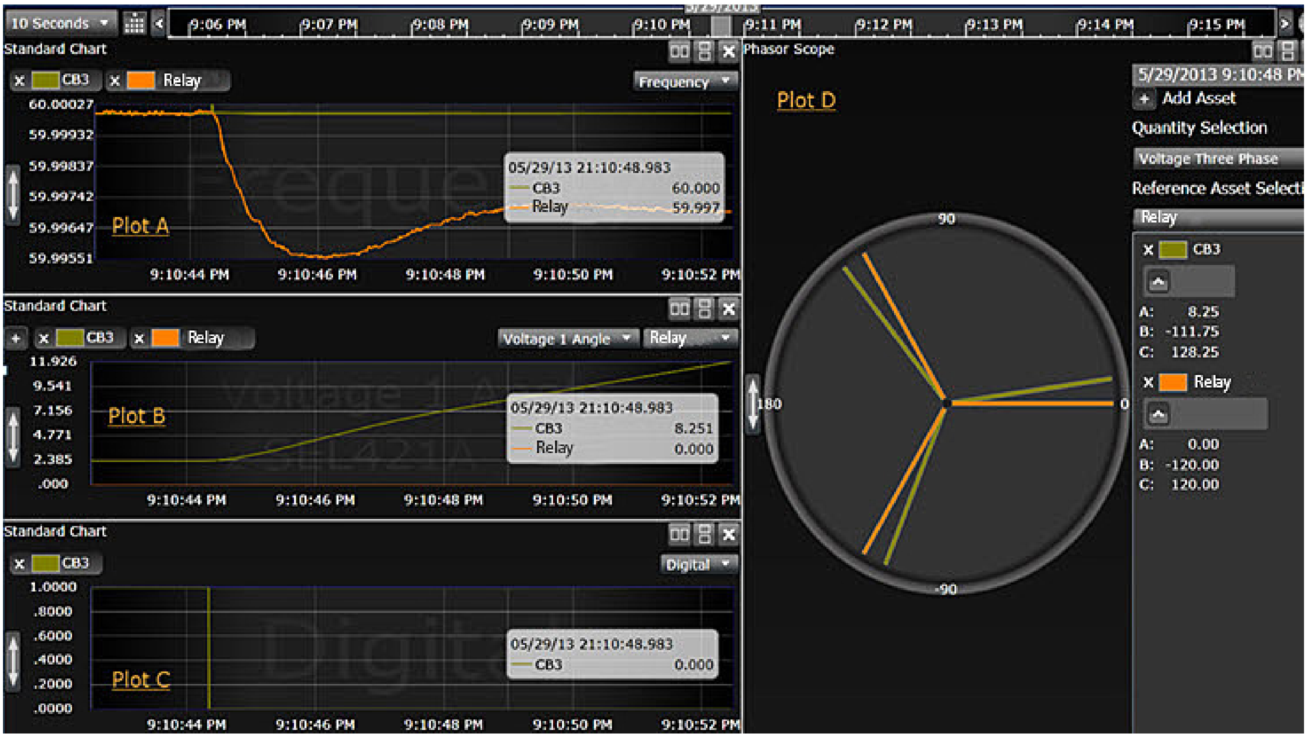

Fig. 7. Synchrophasor-Based Visualization (Phase Angle)

B. Synchrophasor-Based Decoupling Protection

It was observed that the local-based protection will not operate correctly for the system conditions when the load flow on the tie lines between the two systems is low and the remote-end breaker opens. During this system condition, because the tie line from Manifa CPF to SEC is floating (no load flow on the tie lines), the local operating quantities such as voltage, frequency, DFDT, and fast DFDT will not see adequate change to operate. For this system operating condition, the remote substation information and breaker status are required in order to correctly determine the islanding condition. As shown in Fig. 7, it was verified that as soon as the remote-end breaker opens, the external system (CB3 SEC supply breaker) and local Manifa system (Relay) start slipping as they are islanded. The two systems can have a small slip, but the angle between the two systems increases. The faster the two systems slip, the easier it is to detect the system islanding condition. Plot B in Fig. 7 shows the angle difference between the two systems as a function of time for the very low load flow system condition between the Manifa and SEC systems. During a normal operating condition, there is a difference of 2.38 degrees in the two systems. CB3 opening in Plot C signifies the opening of the remote-end breaker. Plot B shows that the angle between the two systems increases slowly to 8.25 degrees in almost 4 seconds. Plot A shows the frequency of the external and Manifa systems. Plot D shows the same angle difference information on a per-phase basis. Design and logic verification using wide-area synchrophasors improves this design [9].

Fig. 8 shows the proposed system configuration for the synchrophasor-based decoupling scheme. The Saudi Aramco Manifa substation has dedicated fiber communication in service with the remote Abu Hydriyah water supply 115 kV substation. Abu Hydriyah water supply is a load substation and is connected to an SEC 380 kV grid. Synchrophasor communication between the two substations at 60 messages per second is possible because direct communication between these two Saudi Aramco substations already exists. Abu Hydriyah water supply is approximately 90 kilometers and two buses from the Manifa substation. Abu Hydriyah water supply provides external grid voltage and angle reference to the Manifa CPF substation via the synchrophasor logic controller at the Manifa end and collects synchrophasor quantities from both local and remote substations.

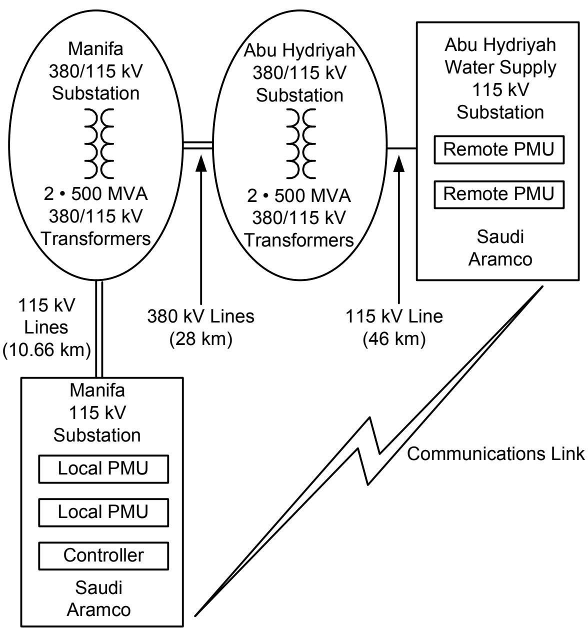

Fig. 8. Future Wide-Area Synchrophasor Solution

V. IN-SERVICE TEST AND RESULTS

The Manifa CPF system was tested for in-service operation of the islanding scheme. For this test, one unit at Manifa CPF was operating at 152 MW with a local load of 15 MW and 130 MW of export. When the remote-end breaker was opened, the scheme operated at fast DFDT and islanded the Manifa system from the external system conditions. This test validated the islanding scheme operation during factory closed-loop testing.

The generation unit runback was also successful, as shown in Fig. 9. The CGT 1 unit was ramped back from 150 MW to 20 MW. The load on the line was approximately 655 A when the remote-end breaker opened. The 655 A of load corresponds to $P = 1.7232 \bullet (0.655\ \text{kA}) \bullet (115\ \text{kV}) =$ ~130 MW of line flow. Local generation is 152 MW, and local load is 15 MW. The system was stable after this operation.

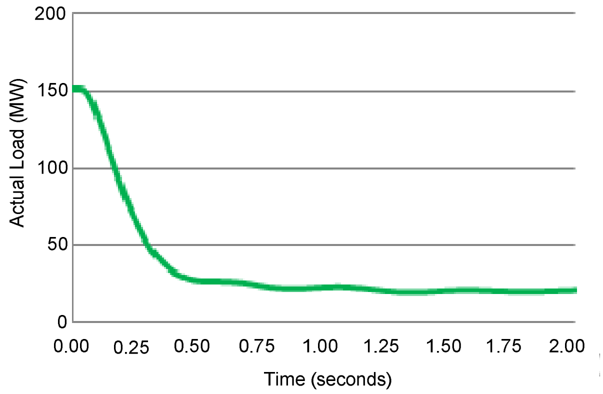

Fig. 9. Generator Runback During CGT 1 Islanding Test

The event analysis, as shown in Fig. 10, indicates that during the in-service test on July 3, 2013, fast DFDT operated via PSV08. After the delay of 5 cycles, the fast DFDT protection trip asserted via PCT11Q. OUT201 and OUT202 tripped Trip Coils 1 and 2 of the breaker A601. The same test was also performed on the second line on August 19, 2013, and results matched the factory test. This in-service test validated the design and operation of the overall scheme and trip assert.

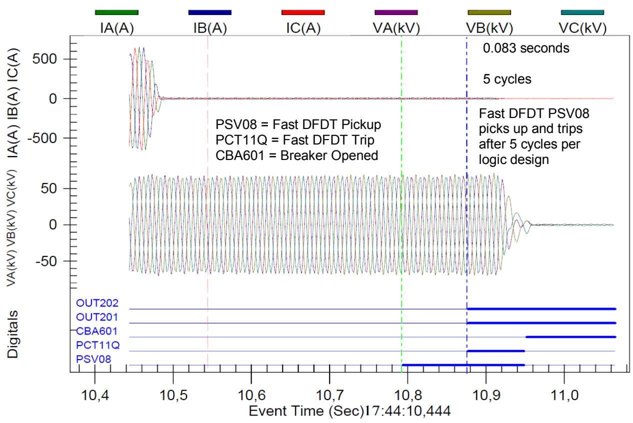

Fig. 10. Fast DFDT Operation for Remote-End Breaker Open

Fig. 11 documents the results from the closed-loop testing using real-time digital simulation and field testing. The response curves of the generator were subsequently further tuned to improve the governor response curve. Additional field data and response monitoring can help in further improving the real-time system model of Manifa.

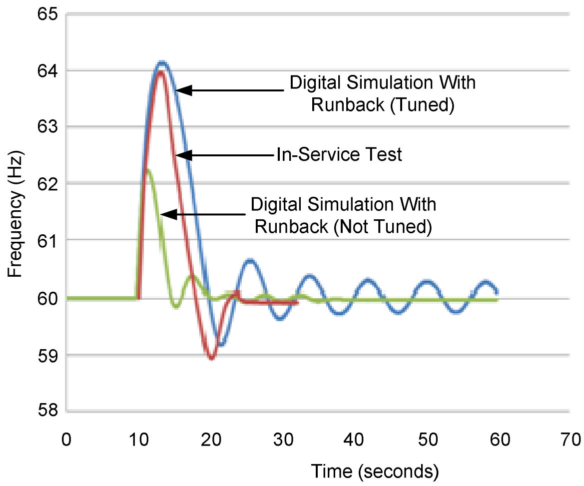

Fig. 11. Islanding CGT 1 Generator Runback Comparison

Fig. 12 shows that the CGT 1 speed reached a high of 3,838 rpm and low of 3,535 rpm during this speed in-service test on July 3, 2013. This corresponds to 63.9 Hz at high frequency and 58.9 Hz at low frequency.

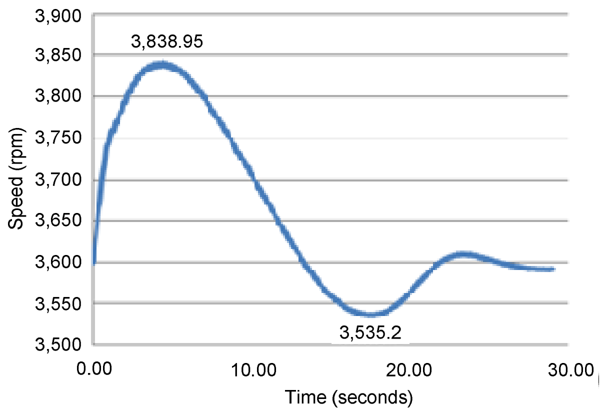

Fig. 12. CGT 1 Runback Speed Trend

Fig. 13 shows the system condition before and after the remote-end breaker opened. During normal system operation, two 115 kV buses are not connected at the Manifa end. Line 1 exports power to SEC, and CGT 1 is in service with a generation of 152 MW and 15 MW of local load. Line 2 imports 60 MW from the utility and maintains the local load.

Fig. 14 shows the A613 and A614 breakers opening at the remote utility SEC end and fast DFDT operation at the Manifa end. Fast DFDT detection on Line 1 opens breaker A601 at the Manifa end. The islanding only operates breaker A601 as designed (there is no impact on Line 2), and the 60 MW load still continues to be fed from a remote SEC substation on Line 2.

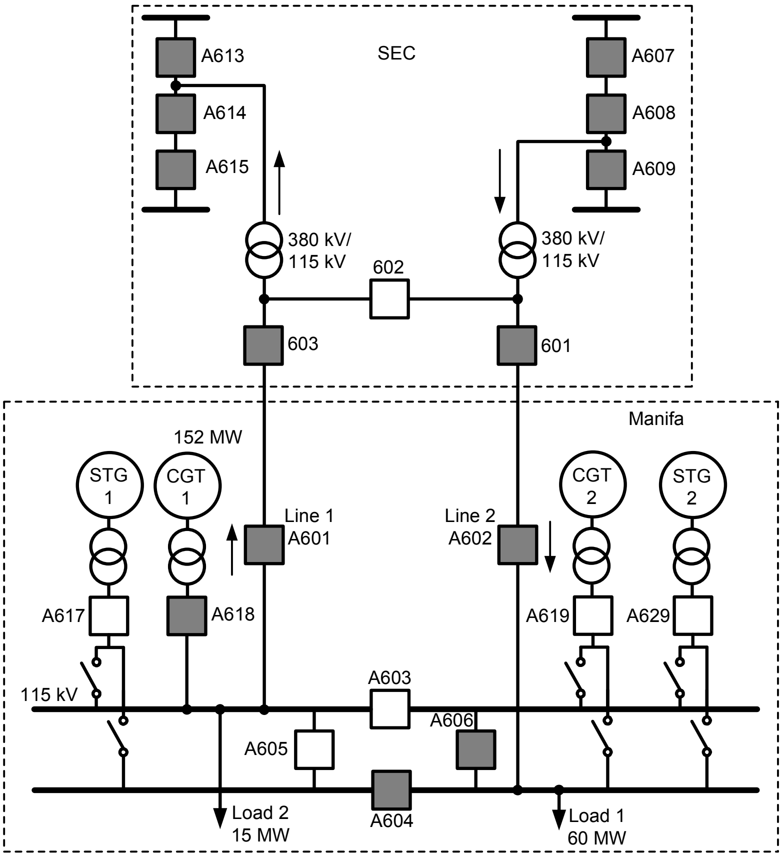

Fig. 13. System Configuration Before Remote-End Trip

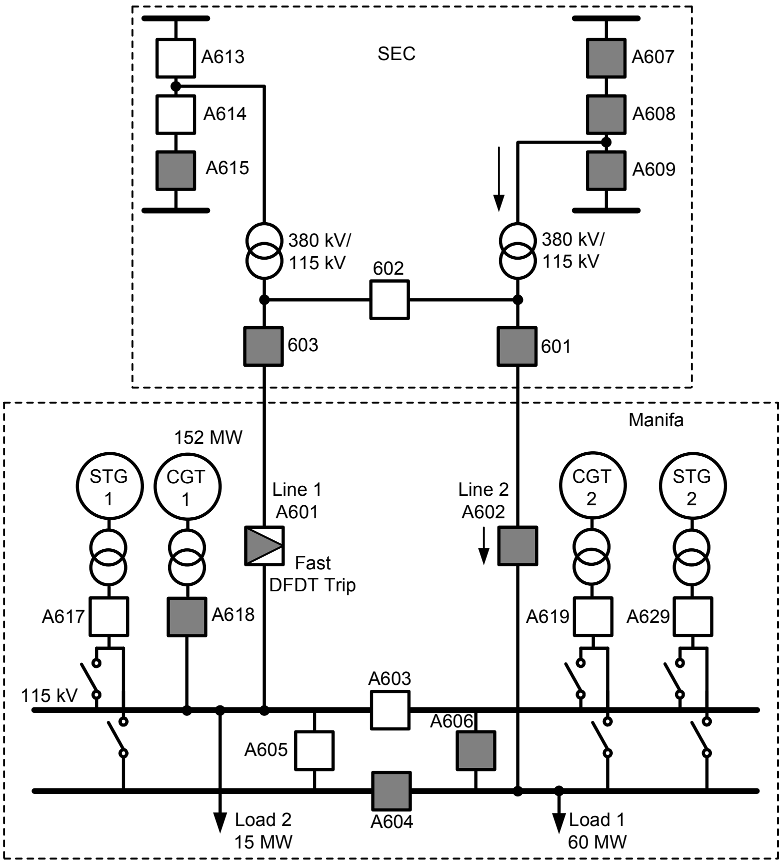

Fig. 14. Fast DFDT In-Service Operation

VI. CONCLUSION

Manifa CPF is the fifth largest oil field in the world. Reliable power system operation is very critical for various system operating conditions. Correct operation of a local or wide-area islanding scheme can help improve the system operation and reliability. The present scheme, designed based on local quantities, can detect and operate for various system operating conditions. A wide-area scheme is required for certain operating system conditions (i.e., low load flow on the intertie [9]). Real-time digital simulation, model validation, closed-loop testing, and on-site design verification help validate the design. The installed scheme is scalable and can be easily upgraded for wide-area monitoring and control.

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VIII. VITAE

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