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Hawaiian Electric Company

Investigation of 2006 Oahu Island-Wide Power Outage
PUC Docket Number 2006-0431

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Executive Summary

The State of Hawaii experienced a 6.7 magnitude earthquake west of the island of Hawaii at about 0707 hours on Sunday, October 15, 2006 (epicenter) and 0708:23 hours (Oahu). This was the strongest earthquake recorded in Hawaii in 23 years. According to the Hawaii Volcano Observatory, a second earthquake (6.0 magnitude) occurred approximately seven minutes later. Associated power system events led to island-wide blackouts for Hawaiian Electric Company, Inc. (HECO) on Oahu and Maui Electric Company, Ltd. (MECO) on Maui, although there was little apparent seismic damage to the electric systems on either island. Hawaii Electric Light Company, Inc. (HELCO) on the island of Hawaii maintained partial service with an isolated section, or "island" of generation and customer load in the Hilo area.

On Oahu, HECO restored power to all circuits by about 0155 hours on October 16, with pocket outages restored as they were identified through the morning and into the early evening of October 16. MECO had restored service to the majority of its customers by 1315 hours and the remaining customers by 1407 hours on October 15. HELCO had restored service to the majority of its customers by 1200 hours with the remaining customers restored by 2300 hours on October 15.

POWER Engineers, Inc. (POWER) was retained to investigate the causes of the outage on Oahu and provide professional opinions on the reasonableness of the responses of the HECO staff during the event and during power restoration. POWER's principal investigators, experts in power delivery systems and generation plant design and operation, traveled to Oahu on November 6 to November 10, 2006 and again on December 4, 2006 to discuss the events with the HECO staff, conduct field visits and gather information relevant to the events of the power outage and restoration on Oahu. Additional information was gathered via discussions over phone,

through extensive follow up information requests, and analysis of system drawings and control schematics, relevant Company logs, studies and records, personnel interviews, and other applicable system documentation.

In summary, we find:

- The HECO system was in proper operating condition and appropriately staffed by personnel at the time that the earthquake struck. The unusually strong earthquake was the direct and proximate cause of the island-wide outage, setting in motion a series of events (through the operation of automatic relays and through operators' actions to protect the equipment) which resulted in loss of generation that eventually led to the system shutdown.
- In POWER's opinion, the HECO personnel reacted to the circumstances in a reasonable, responsible and professional manner. They applied training and experience in reacting properly to the changing system conditions based on the existing system configuration and established HECO operating practices to attempt to prevent the island-wide outage and to restore power as quickly as practical.
- In particular, after the complete shutdown of the system, a critical and prudent decision was made to simultaneously black start units at Kahe and Waiau power plants in parallel, which allowed the restoration to proceed as expeditiously as possible without the setbacks that would have resulted from delays that were in fact encountered at Kahe plant.
- In the restoration, HECO operated reasonably and in the public interest by following a systematic, orderly and methodical approach to add customer load to the system, allowing adequate time to inspect the system for earthquake damage, stabilize the operation of the generating units, and stabilize frequency and voltage on the grid.
- With the understanding that no system event will ever be identical to the one before it, we do make some specific recommendations which can be found at the end of this Executive Summary and in Section 5 of the report.

Discussion of Findings

The Hawaii Public Utilities Commission issued PUC Order No. 22986, Docket No. 2006-0431 ("PUC Order") requiring an examination of whether HECO, HELCO and MECO acted reasonably and in the public interest prior to and during the power outages. The PUC Order, Section II.C Preliminary Issues, page 8 and page 9, established the scope for this investigation.[1] This report addresses the following issues with respect to HECO.

1. *Aside from the earthquake, are there any underlying causes that contributed or may have contributed to the power outages?*

   We believe that the main underlying cause of the outage was the seismic action of the earthquake triggering mercury switches on generating units Kahe 5 and Kahe 6. These switches were used in the original equipment manufacturer's design to sense "Low-Low Fluid Level" on the Electro-Hydraulic (E.H.) governor system that regulates steam flow to the turbines. These switches on Kahe 5 and Kahe 6 operated the "Low Fluid Level Lockout" relays that prevent the E.H. system pumps from restarting to maintain the required operating hydraulic pressure, thereby leading to the loss of power from Kahe 5 and Kahe 6. The HECO system would have survived the trips of Kahe 3 and Honolulu 8: however the shutdown of both Kahe 5 and Kahe 6 exceeded the spinning reserve of the remaining units.

   The same style of mercury switches are installed in other fluid level monitoring applications in the Kahe 3, Kahe 4, Kahe 5 and Kahe 6 generating units, specifically on the feedwater level alarms and many of these alarms falsely activated during the earthquake.

[1] We understand that the preliminary issues were adopted as the issues for Docket No. 2006-0431 by Order No. 23155 (filed December 21, 2006).

2. *Were the activities and performance of the HECO Companies prior to and during the power outages reasonable and in the public interest? Specifically, were the power restoration processes and communication regarding the outages reasonable and timely under the circumstances?*

HECO's performance prior to and during the outage demonstrated reasonable actions in the public interest. The investigation found that prior to the outage, the system had all transmission lines in service and the appropriate generation available to supply load and reserves according to the approved HECO operating procedures. HECO had been consistently updating load shed studies applicable to system performance under a low frequency event. They have performed regular training; such as emergency response Incident Command exercises; the "System Dynamics and Generator Unit Response During Normal Operations and System Disturbances" training for the dispatch operators, generating unit control operators, and other operations staff; and black start training at Kahe power plant.

The actions of the HECO staff were certainly reasonable and timely, in the best interests of the public, and amounted to a good level of performance under the circumstances. With the advantage of calm hindsight, we can see that in a few cases there are details in which slightly different courses of action could have been taken. But we are not aware of any case where actions could be described as imprudent or likely to cause injury, or damage. In our opinion, actions by HECO personnel were reasonable, responsible and conducted in a professional manner.

The system restoration plan developed after the outage by the operations staff was reasonable based on steam generation as the first units to start and HECO management's historical knowledge of critical restoration issues. The plan appears to have been well executed by the

primary trouble men (PTM), construction and maintenance crews, and substation crews. The pace of the restoration was balanced against the risk of tripping the generators restored to service, which would have required the system to be re-sectionalized and then re-started. The HECO internal communication systems operated adequately and did not hamper restoration.

The power plant staff exercised reasonable judgment in the planning and execution of the black-start procedures and responses to equipment failures encountered during a stressful time. The black start process was slowed due to equipment failure, troubleshooting and trips of the black start generators. The decision to proceed with black start simultaneously at Kahe and Waiau minimized the time required to restore black start power to the system. With this experience, we feel that HECO could improve, through the incorporation of some contingency planning and scenarios based upon recent events, training on black start procedures.

The operator trips of Kahe 3 and Honolulu 8 were reasonable and in the public interest considering the alarms, observations and previous experience, and considering that they each only had one turbine on line to consider as the source of the vibration. The operators also expected, and rightly so, that generation loss due to operator trips of Kahe 3 and Honolulu 8 were well within the HECO spinning and quick load pickup reserve at the time they tripped their units. They acted in good faith to minimize damage to the turbines that could result in unit outages of several months. Other operators with two units running also initially believed they had turbine vibration, but in the evaluation to determine which of the two units was causing the shaking they found that neither unit had an activated vibration alarm.

As a result of the seismic activity, the switches on Kahe 5 and Kahe 6 operated the “Low Fluid Level Lockout” relays that prevent the E.H. system pumps from restarting to maintain

the required operating hydraulic pressure, thereby leading to the loss of power from Kahe 5 and Kahe 6. The fact that the Kahe 5 and Kahe 6 operators did not immediately respond to the "Low Fluid Level Lockout" alarms is understandable given that they were responding to a multitude of other alarms and system conditions[2]. However, even had the Kahe 5-6 operators recognized the significance of the "Low Fluid Level Lockout" alarm and that the E.H. Lockout had tripped, it is very doubtful that, in the three to six minutes available before Kahe 5 and Kahe 6 lost power, they could have performed a proper inspection and determined that the "Low Fluid Level Lockout" trip was due to a false indication by a mercury switch caused by the seismic shaking.

Our opinion is that operators for units Kahe 1-2 and at Waiau Power Plant exercised reasonable judgment in their decisions to attempt to "island" Kahe 1 and Kahe 2 and to keep the Waiau units connected to the grid, given the system circumstances, configuration of the 46 kV loads at Kahe compared with that of Waiau and HECO's operating procedures and requests by the dispatchers.

During the time of the event, it appears that the Supervisory Load Dispatcher (SLD) and Load Dispatcher (LD) took appropriate actions, using previous training and experience, to quickly and correctly determine that after the loss of power from Kahe 3 and Honolulu 8 that such loss would affect the system spinning reserve and called for startup of the Waiau combustion turbines (CTs) and the substation distributed generators (DGs) to make up the lost reserve. When Kahe 5 and Kahe 6 lost power the SLD quickly realized that the system was in jeopardy and initiated manual load shedding to try to salvage a portion of the system

[2] The significance of a "Lockout" relay in the utility industry is that it enforces the standard requirement for operators to inspect the condition of the equipment and verify the underlying cause of the relay operation. Once the fault is located and repaired or the system is inspected and or tested and found to be in operating condition, the "lockout" relay is manually reset and the system restored to operational status.

to provide restart power. Their actions were within the HECO Operations Division Policy Manual (ODPM) guidelines and POWER's only concern with their actions is with respect to the extended low frequency operation of the turbine-generator units.

After a complete shutdown of the grid, a critical and prudent decision was made at about 0809 hours on October 15 to black start units at Kahe and Waiau Power Plants in parallel. This decision restored initial power to the system at 1154 hours from Waiau Power Plant. If black start efforts had been solely focused at Kahe Power Plant, initial power to the system would have occurred at approximately 1430 hours. During initial attempts to restore black start power to the plant auxiliaries at Kahe, there were some problems in configuration of the black start generators and plant auxiliary system. Part of this was due to inexperience of a couple of plant staff in disconnecting the diesels from the grid and properly configuring the selected steam unit auxiliaries. However, these initial events did not significantly impact the system start time as this was occurring in parallel with other activities. A trip of the Kahe black start generators when Kahe 3 had fires in, due to an overload from auxiliaries, resulted in a delay bringing Kahe plant on-line and thus, Waiau 6 was the first unit on the bus. It must be recognized that black start of the Kahe and Waiau power plants is an activity that has rarely been required, the last instance being 15 years ago. Familiarity with the procedures for such significantly complex process can only come through training, rather than developing proficiency by actual application, and the training is limited by how much can be simulated while the other units are operating.

Once the black start process had been successfully completed, HECO operated reasonably, timely and in the public's interest by following a systematic, orderly and methodical approach to add customer load to the system to allow adequate time to inspect the system for earthquake damage, stabilize the operation of the generating units, and stabilize frequency

and voltage on the grid. If the dispatchers attempted to add larger blocks of load, especially this early in the load restoration process, the likely result would have been much larger frequency and voltage fluctuations than experienced during the restoration. The control operator would then have experienced more difficulties controlling the operating generating units and stabilizing system voltage and frequency. Pickup of larger load blocks could also have resulted in a trip of Waiau 6 and requiring that the black start sequence be started over from the beginning including re-sectionalizing of the electric grid. This would have resulted in a delay of several hours with significant adverse consequences for the HECO and customer equipment operating on emergency power, and for critical facilities.

We have briefly reviewed the reports of the experiences of the electrical systems on Maui and the island of Hawaii on October 15, 2006, to consider possible comparisons with Oahu, particularly in regard to the duration of interruptions of supplies to consumers. We note that the generation technologies employed, the much smaller electrical systems, and the smaller sizes of individual generating units on Maui and the island of Hawaii, are quite different from those on Oahu. For this reason, the response to an exceptional system event such as that experienced on October 15, and the times for re-starting large-scale generation, can also be expected to be quite different. Our present conclusion, in advance of any detailed reviews of the Maui and HELCO systems, or of their responses to the October 15 earthquake, is that it is difficult to make a direct comparison between the HECO, MECO and HELCO experiences, and it could be misleading to do so.

3. *Could the island-wide power outages on Oahu and Maui have been avoided? What are the necessary steps to minimize and improve the response to such occurrences in the future?*

In POWER's opinion, the HECO personnel reacted to the circumstances in a reasonable, responsible and professional manner. They applied training and experience consistent with HECO operating practices in a deliberate effort to prevent the island-wide outage on Oahu and to restore power as fast as practical. (POWER's opinion on the Maui outage will be provided upon completion of the separate study of the Maui outage due on March 30, 2007.)

Kalaeloa Combustion Turbine 2 remained on line, supplying local auxiliary or 'house' load for some time, until it had to be shut down for operational reasons. In the case where one or both of the Kalaeloa combustion turbines continue to operate following a system disturbance and isolate or 'island' to local load, they might be used to restart the grid, if the 138 kV substation equipment is reconfigured to allow them to close on the "dead" bus bar of the transmission system. This is one suggestion on how to minimize and improve response to another island-wide outage.

Recommendations

The detailed recommendations from Section 5 are summarized below.

1. Review the "E.H. Low Fluid Lockout" control logic schemes for the motors driving the E.H. pumps for the main steam valves for Kahe 5 and Kahe 6. Evaluate replacement of the 86 LFT lockout with a non-latching relay while maintaining plant safety and proper operation. The controls should retain the present automatic tripping of the motors on low-low fluid levels and prevent re-starting while those low-low levels continue to be detected. The low-low fluid level alarm should also be maintained as long as the low fluid level condition is detected. We would like to note that HECO is presently acting on this recommendation.
2. Investigate replacing the mercury-type level switches presently used in the E. H. system and in the horizontal feed water heaters for the Kahe units, with a type or types less likely to give false indications under earthquake conditions.

3. Assess the possible employment of the Kalaeloa combined cycle block, to allow the use of its combustion turbines to re-power "black" transmission circuits.
4. Undertake a study, in the light of the experience of October 15, 2006, and subsequently update, to the extent appropriate, its low frequency tripping scheme based on the results of the study.
5. Assess the minimum frequencies at which each of HECO's steam turbine generating units can safely operate at full load, including a determination of reasonable durations of full load operation at various frequencies below the 60 Hz nominal.
6. Visually inspect the last row of Low Pressure (LP) turbine blades on Waiau 5, Waiau 7, Waiau 8, Kahe 1, and Kahe 2 for cracking and/or lacing wire damage by viewing from the exhaust spaces, or when the units are offline. We understand that Kahe 1's LP turbine blades were inspected during a scheduled overhaul after the earthquake. Inspection of the Kahe 1 LP section has not revealed any visible damage to Kahe 1.
7. Assess the system restoration process following an island-wide blackout to determine the best order for generator startup that would allow load to be added in a safe and expeditious manner while carefully retaining frequency and voltage stability. This study should take into account 1) the sequencing of the restoration for facilities critical to stabilizing the HECO system, 2) address practical priority restoration of critical customers and support services on Oahu, 3) the effect of the HECO 138 kV transmission system capacitance under no-load or light-load on system voltages during restoration, 4) flexibility in the restoration process to account for differing contingencies, and 5) the use of the planned Campbell Industrial Park combustion turbine (which will have black start capability) and possible use of the Kalaeloa CTs.
8. Evaluate black start procedures and training to account for equipment failure contingencies and communications across simultaneous units black starting.

9. Assess the feasibility of providing additions to physical equipment and/or software for capture and storage of a reasonable dataset (e.g., a one hour snapshot period) for all Distributed Control Systems (DCS) information, for each generating unit equipped with a DCS.