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HAWAII ELECTRIC LIGHT COMPANY

Investigation of 2006 Hawaii Island 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). This was the strongest earthquake recorded in Hawaii in 23 years. According to the Hawaii Volcano Observatory (HVO), 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 on the east side of the island of Hawaii.

On the island of Hawaii, all transmission lines and distribution feeders were closed in by 1245 hours (5.6 hour outage), with the exception of those where the circuits or substations required repairs prior to restoring service. HELCO had restored service to the remaining customers by 2300 hours on October 15.

POWER Engineers, Inc. (POWER) was retained to investigate the causes of the outage on the island of Hawaii and provide professional opinions on the reasonableness of the responses of the HELCO 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 Hawaii on January 10-12, 2007 to discuss the events with the HELCO staff, conduct field visits and gather information relevant to the events of the power outage and restoration on Hawaii. Additional information was gathered via telephone discussions, through follow up information

requests, analysis of system drawings, review of relevant Company logs and records, statements of personnel, and other applicable system documentation.

In summary, we find:

1. The HELCO and Independent Power Producer (IPP) power plants, Kanoiehua Operations Control Center (KOCC) and transmission system were properly configured, dispatched and staffed for normal operations on the morning of Sunday October 15, 2006 at 0700 hours.
2. In POWER's opinion, the HELCO 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 system configuration and followed established HELCO operating practices to prevent an island-wide blackout and restore power as quickly as practical to the areas that were out of service.
3. The separation of the transmission system from Kealia in South Kona to Pepekeo on the Hamakua coast was primarily the result of the earthquake triggering auxiliary relays in the transmission protection systems due to seismic shaking. These lines were quickly closed back in by the System Operator using the Supervisory Control and Data Acquisition (SCADA) system following the stabilization of the remaining energized portion of the power system.
4. The manual trip of Puna Steam Unit by the control operator was reasonable and prudent according to HELCO's established operating practices to prevent damage to the machine and risk potentially extensive down time for repairs. Following the unit trip the boiler steam pressure was preserved to minimize the restart time when the system had stabilized.

5. The automatic generator vibration trips of the two Hamakua Energy Partners (HEP) combustion turbines (CTs) were valid to protect the units as the minimum mechanical clearances were exceeded. When this occurs, the machine is in danger of sustaining damage, even if the source of the problem is external shaking.
6. The trip of the Hill 5 boiler is thought to be related to the earthquake but we have not been able to positively identify a cause for the fuel oil trip. Hill 6 had earthquake caused trips of the boiler feed-water pumps from liquid level switches on the deaerator level alarm, but the operators were aware of this possibility and quickly reset the pumps. The boiler feedwater pump trips did not result in the trip of the Hill 6 turbine.
7. The superheated steam leak on Hill 6 that required the unit to be tripped is believed to have been caused by high pressure steam transients due to the extreme system frequencies following the loss of transmission and load during the earthquake.
8. The under frequency load shed scheme operated as designed and prevented the east Hawaii power system from collapsing when the Puna Steam, Hill 5 and Hill 6 generators dropped off line. The System Operator made it a priority to restore portions of the under frequency load shed scheme which again operated later for under frequency when Hamakua Energy Partners Combustion Turbine 1 (HEP CT-1) and the associated steam unit tripped offline again at 1009 hours.
9. Activation of eight transformer sudden pressure protection schemes which tripped the transformers, and opening of transformer primary fuses at 15 substations that were directly associated with the seismic activity prolonged system restoration due to the need for HELCO personnel to travel to the affected substations and manually reset the equipment prior to re-

energizing. This prevented the System Operator from remotely starting diesel generators and CT-5 at Keahole and restoring load at the other substations until field personnel completed equipment inspections and reset the lockout relays.

10. Communications internal to HELCO and with the Civil Defense agencies through the Emergency Operation Center worked very well. The microwave, VHF and UHF communication system operated properly. The only indication of a failure of the internal communication system was with the paging/text messaging system which is increasing in importance, but on the day of October 15th did not pose a hindrance or delay in HELCO's ability to respond to the partial outage and efforts to restore the system. This paging/text messaging system presently depends on equipment routed over Maui to HECO equipment on Oahu and has potential failure modes unrelated to the status of the system on Hawaii.

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 HELCO.

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

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).

We conclude that the main underlying cause of the outage on the western side of the island was the earthquake acting on transmission protection scheme auxiliary relays that tripped the transmission lines and separated portions of the system.

The Hill 6 power plants had equipment trips associated with liquid level switches that were activated by the earthquake, but these did not result in a unit trip.

HEP power plant, generating 58 MW at the time, was islanded by the earthquake-caused transmission line trips, but also had both combustion turbines tripped by its vibration protection due to the earthquake action. These were valid trips to protect the generators.

In addition, there were eight substation transformers where the sudden pressure protection scheme activated lockout relays and 15 substations where transformer primary fuses opened due to the earthquake action. These events required HELCO personnel to travel to the substations, inspect the equipment for damage, reset the relays, and reconnect the fuses in order to enable the System Operator to complete the restoration.

2. *Were the activities and performance of the HELCO 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?*

The actions of the HELCO staff were reasonable and in the best interests of the public, and amounted to a good level of performance under the circumstances. In POWER's opinion, the HELCO personnel reacted to the circumstances in a reasonable, responsible and professional manner. The system operations and power plant staff applied their training and experience in

reacting immediately and properly to the changing system conditions to prevent an island-wide blackout, protect generation plant equipment, and restore power as quickly as practical. We have considered SCADA reports for the transmission system, load shedding scheme settings, HELCO's breaker trip analysis, relay event reports and personnel interviews following the earthquake on the morning of October 15. We also reviewed statements of power plant operators and conducted direct interviews of various HELCO personnel. In HELCO's case, we have not identified any instance for which we would offer an alternative action. We are not aware of any case where actions could be described as imprudent, or likely to cause injury or damage. There can be no doubt that the operating staff, especially in the KOCC and power plants, during and immediately after the earthquake at 0708 hours on October 15th, experienced conditions outside their normal operations experience. The situation was complicated and confused by the plethora of alarm indications, the transmission system tripping open, transformer protective devices operating, generation tripping, power stabilization of the remaining energized grid and generation and the subsequent need to quickly restore the system. The HELCO personnel acted professionally throughout the event and restoration applying their training and experience to their assigned tasks during a distinctly extraordinary event. The system restoration plan developed by the operations staff was prioritized, reasonable and well executed. The pace of the restoration was very aggressive and well executed where the system could be remotely closed to restore the transmission to generation plants and load centers. System integrity assessment, identification of damage, and repair were expedited as much as possible, considering the staffing assignments and the initial road closures, to safely restore service to all customers as quickly as possible.

Communications internal to HELCO, with the IPP generation plants, and with the Civil Defense agencies through the Emergency Operation Center (EOC) worked very well.

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?*

With respect to Hawaii, an island-wide outage was avoided through the separation of the transmission system, the ability of the system to quickly start and connect generation, the quick actions of the System Operator to maximize the connected generation, and operation of the load shed scheme when Puna Steam, Hill 5 and Hill 6 went off-line. HELCO has several systems in place that allow the System Operator to take very fast action in the event of loss of generation and they have a very extensive under frequency load shed scheme, which provides significant flexibility to survive these types of events.

Recommendations

We offer the following recommendations to prevent miss-operation of equipment and keep the system operation in the control of the System Operator and the designed under frequency protection schemes.

The detailed recommendations from Section 5 are summarized below.

1. Evaluate the transmission relaying equipment, mounting methods, and operational schemes related to the employment of ABB, Style AR auxiliary relays to provide relay protection schemes that are less likely to miss-operate during seismic events.
2. Investigate and evaluate the likely miss-operation of the Qualitrol Fault Pressure sensors with magnetic target relays protective equipment installed on HELCO transformers. Determine appropriate sensor/relay replacements or scheme changes that reduce the likelihood of the tripping of substation and generator step-up transformers due to miss-operation during seismic events.

3. Assess the transformer primary fuse holders to determine whether there is another model or changes to its mounting and configuration to make fuses and their holders less susceptible to shaking open during earthquakes.

4. Assess application of mercury liquid level switches on the deaerator level alarms, used in Hill 6, and determine the appropriate equipment to provide elements that are less susceptible to operation due to external shaking.

5. Assess the internal HELCO communications for paging/text messaging to determine potential failure modes and appropriate solutions.

Introduction

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). 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 east Hawaii area.

HELCO had restored service to the majority of its customers by 1245 hours with the remaining customers restored by 2300 hours on October 15.

POWER Engineers, Inc. (POWER) was retained to investigate the causes of the partial outage on Hawaii and provide professional opinions on the reasonableness of the responses of the HELCO 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 Hawaii on January 10-12, 2007 to discuss the events with the HELCO staff, conduct field visits and gather information relevant to the events of the power outage and restoration on Hawaii. Additional information was gathered via discussions over the phone, through follow up information requests, analysis of system drawings, review of relevant Company logs and records, statements of personnel, and other applicable system documentation.

The Hawaii Public Utilities Commission issued PUC Order No. 22986, Docket No. 2006-0431 (“PUC Order”) requiring an examination of whether Hawaiian Electric Company, Inc. (HECO), Hawaii Electric Light Company, Inc. (HELCO) and Maui Electric Company, Ltd. (MECO) (collectively “the HECO Companies”) acted reasonably and in the public interest prior to and during the power outages. The PUC Order, Section II.C Preliminary Issues, pages 8 and 9, established the scope for this investigation.

The PUC Order identified the following investigation subjects:²

1. Aside from the earthquake, are there any underlying causes that contributed or may have contributed to the power outages?
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?
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?
4. What penalties, if any, should be imposed on the HECO companies?³

² We understand that these four issues were adopted in Order No. 23155 (filed December 21, 2006) in Docket No. 2006-0431.

³ This report does not address this subject.

In addition, a reference under II.A Discussions, at the bottom of page 7 states: "... there may be some benefits to being able to compare the different utility systems on each of the three affected islands. These differences can and should be explained in the context of the outages and the varying restoration times." The comparison is presented in the HECO, HELCO, MECO Outage and Restoration Comparison report being submitted concurrently to the PUC.

From the PUC Order, HELCO established the main statement of work for POWER Engineers to investigate and provide expert opinions with respect to the partial blackout and restoration on Hawaii. POWER's investigation focused on five primary topic areas for the HELCO transmission system, dispatch center and power plants.

These five primary topic areas are:

- System configuration prior to the event, to include operating procedures and prior training relevant to the event.
- Transmission system, dispatch center and power plant operator actions and automatic protection system action during the interval between the time when the earthquake seismic waves reached Hawaii and the onset of the partial system blackout.
- Restoration of the power grid from the time the Hilo system stabilized until restoration of service to all customers on October 15.
- Comparison of the root causes and restoration times of the HECO, HELCO and MECO outages.
- Assessment of the HELCO internal communications.

2 Sequence of Events

2.1 Background

Transmission and Distribution System

The HELCO transmission and distribution system consists of twenty 69 kV transmission substations and fifty-four distribution substations, twenty-eight 69 kV transmission lines, six 34 kV sub-transmission lines, and 126 distribution feeder circuits. The majority of 69 kV and 34 kV circuits are interconnected with redundant circuits that provide multiple options for supplying power to the distribution substations to increase reliability. One of the 69 kV and one of the 34 kV circuits are in a radial configuration without redundant circuits that provide backup sources of power. These 69 kV and 34 kV circuits can be remotely operated by SCADA control by the dispatch center operator. HELCO has an extensive automatic under frequency load shed (UFLS) scheme with 9 steps that would shed an estimated 90 MW during a morning peak.

Operations

HELCO typically operates with a minimum “regulating reserve” – up and down - of approximately 6-7 MW. This means that they have generators on line and running with a total capacity to produce approximately 6-7 MW more than the load in order to absorb typical load fluctuations. The regulating reserve may differ from the 6-7 MW norm under conditions of high as-available energy production, periods of load ramping up or down, or special dispatch considerations. Generators are brought on line (or taken off line) in preparation for the expected load variations throughout the day and to maintain the regulating reserve. This operating philosophy is perfectly reasonable for a relatively small electrical system like that at HELCO with relatively high energy costs, as this strategy reduces energy costs incurred by running more generation at lower efficiency levels to provide larger reserves. It is noted that the system is

therefore not operated with a “spinning reserve” sufficient to cover the loss of the largest single generating unit, which is generally the operating philosophy on larger electrical systems such as the HECO system on Oahu. Instead, HELCO relies on a combination of fast start diesel engines and underfrequency load shedding to stabilize the system following the loss of the largest unit. Approximately 276 MW of firm generating capacity is currently installed on the island of Hawaii, with an additional 29 MW of wind and hydro power providing as-available energy. Of the 276 MW, 186 MW is owned and operated by HELCO and 90 MW by Independent Power Producers (IPPs). The HELCO and IPP plant capacities are summarized in Table 1.

The KOCC contains System Operations and the dispatch center. The dispatch center has a large wall display and computer screens to show the status of circuit breakers, transmission lines and generators and is staffed by the on-duty System Operator (SO). This system also has an alarm screen that scrolls up when alarms are received. The Energy Management System (EMS) has an Automatic Generation Control (AGC) function which continuously controls the dispatch of a subset of the online generators and displays this information on the wall screen and computer monitors. Only units that are on AGC participate in load following or frequency regulation. Generating units are brought on-line and taken off-line daily according to changing load requirements. Generator designations, capacities and loading on October 15, 2006 just prior to the earthquake are provided in Table 1. The dispatch center has emergency manual load shed which appears as a button on the monitors and wall display screen that allows the System Operator to quickly shed additional load with a single action sequence. This load shed was designed specifically to correct undervoltage conditions in the North Kona/South Kohala area. HELCO also has two “All-Start” buttons which fast start all of the dispersed diesel generators. One button is for on-peak and includes all the diesel generators including Keahole; the off-peak button excludes Keahole due to operational constraints that prevent operation of Keahole diesels between 10 pm and 7 am. For the time of the earthquake, the on-peak button was used and

Keahole diesels were included in the start sequence, although they could not start because they were isolated by the transmission and generator step up transformer relay trips. The four dispersed diesel units are capable of starting within 30 seconds and synchronizing to the system. The nine EMD units take approximately 2.5 minutes to start, warm up and synchronize to the system. They load at a nominal ramp rate of 2 MW per minute, and thus they can be at full load in approximately 4 minutes from startup. HELCO has three “baseyards” located at Kanoelehua, Waimea and Kona that act as staging locations for transmission and distribution service crews and materials.

Relevant Training

HELCO trains operators in advance so that they are prepared for at least one promotion, and at times more, as vacancies are created at the top of the Line of Progression. This ensures HELCO has qualified personnel to fill the vacancies. The qualification training includes doubling up with a qualified operator for a period of 4 weeks followed by solo operations under supervision for 1 month to qualify for the position.

There is a training program for the entry-level operator trainees that includes system theory with classroom modules. This operator trainee program is more lengthy than qualification training for other advancements in the line of progression. The trainee classroom modules are followed by practical tests and inquiries by the shift supervisor, with hands-on experience, to ensure that the operator understands the systems. Then, as with subsequent qualification training, there is a period of double-up training, followed by the on-shift period. For a new operator trainee, the time involved is 4 weeks for the operator book training, 4 weeks double-up training, and 4 weeks on-shift under supervision – but can vary with position and the skills and experience of the individual. This period can also be shortened at time if extra supervision is on shift. For qualification training for promotion to subsequent position, the training is 4 weeks double-up, 4

weeks on-shift. The supervisor on each shift is responsible to oversee and follow up with the training. The supervisor is to go over the training checklists with the operator trainee to assure that the trainee understands the equipment, and its operation as it pertains to the operation of the plant and its function. Training is provided with any changes or upgrades to equipment within the power plant. The Hilo operator line of progression defines the promotion of operators as advancing from boiler operator, to combustion turbine operator, to turbine control operator, to system operator. Thus, a System Operator has previously qualified and worked as an operator at the Hilo side power plants. The Keahole power plant is not included in the line of progression.

2.2 System Conditions at 7:07 AM Sunday October 15th

On Sunday October 15, prior to the earthquakes, the 69 kV transmission and 34 kV sub-transmission systems were in their normal configuration with all lines in service. No transmission maintenance outages were scheduled for the day. The generation commitments for a Sunday morning were normal. Typically, the HELCO base load generation is located on the eastern side of the island and as load increases, units are started at Keahole on the west side of the island. The capacity of HELCO plant in operation immediately before the earthquake was approximately 136 MW, and the system load was 126 MW. The power plant unit status from the EMS archive is provided in Table 1.

The dispatch center was properly staffed according to HELCO operating procedures. The energy management system (EMS) archive indicated a regulating reserve of 10.3 MW. The System Operator was conducting routine monitoring of the system conditions and coordinating the startup schedule of generation, with the operator at Shipman 3 preparing to bring the unit on-line as demand for power began to increase.

Power plant staffing was normal for a Sunday. The personnel were conducting their normal routines of monitoring the plant conditions.

Table 1: Generation Status 0700 Hours October 15, 2006

HELCO Plant	Unit	Fuel Type	Type	Operation	Capability (MW)	Service Date	Status	Output (MW)	Reserve (MW)
Shipman	3	No. 6 Fuel Oil	Steam	Cycling	7.5	1955	Starting	0.0	0.0
Shipman	4	No. 6 Fuel Oil	Steam	Cycling	7.5	1958	Out-Maint.	0.0	0.0
Puna		No. 6 Fuel Oil	Steam	Baseload	15.5	1970	On-AGC	9.9	5.6
Puna	CT-3	No. 2 Diesel	CT	Cycling	20.8	1992	Off	0.0	0.0
Hill	5	No. 6 Fuel Oil	Steam	Baseload	14.1	1965	On-AGC	10.5	3.6
Hill	6	No. 6 Fuel Oil	Steam	Baseload	21.4	1974	On-AGC	20.3	1.1
Kanoelehua	11	No. 2 Diesel	ICE	Peaking	2.0	1962	Off	0.0	0.0
Kanoelehua	15	No. 2 Diesel	ICE	Peaking	2.8	1972	Off	0.0	0.0
Kanoelehua	16	No. 2 Diesel	ICE	Peaking	2.8	1972	Off	0.0	0.0
Kanoelehua	17	No. 2 Diesel	ICE	Peaking	2.8	1973	Off	0.0	0.0
Kanoelehua	CT-1	No. 2 Diesel	CT	Peaking	11.5	1962	Off	0.0	0.0
Waimea	12	No. 2 Diesel	ICE	Peaking	2.8	1970	Off	0.0	0.0
Waimea	13	No. 2 Diesel	ICE	Peaking	2.8	1972	Off	0.0	0.0
Waimea	14	No. 2 Diesel	ICE	Peaking	2.8	1972	Off	0.0	0.0
Keahole	21	No. 2 Diesel	ICE	Peaking	2.8	1983	Off	0.0	0.0
Keahole	22	No. 2 Diesel	ICE	Peaking	2.8	1983	Off	0.0	0.0
Keahole	23	No. 2 Diesel	ICE	Peaking	2.8	1987	Off	0.0	0.0
Keahole	CT-2	No. 2 Diesel	CT	Cycling	13.0	1989	Out-Maint.	0.0	0.0
Keahole	CT-4	No. 2 Diesel	CT	Cycling	22.0	2004	Off	0.0	0.0
Keahole	CT-5	No. 2 Diesel	CT	Cycling	22.0	2004	Off	0.0	0.0
Panaewa	24	No. 2 Diesel	ICE	Peaking	1.0	1997	Off	0.0	0.0
Ouli	25	No. 2 Diesel	ICE	Peaking	1.0	1997	Off	0.0	0.0
Kapua	26	No. 2 Diesel	ICE	Peaking	1.0	1997	Off	0.0	0.0
Punaluu	27	No. 2 Diesel	ICE	Peaking	1.0	1997	Off	0.0	0.0
HELCO TOTAL FIRM GENERATION					186.1			40.7	10.3

Table 1: Generation Status 0700 Hours October 15, 2006, Continued

FIRM CONTRACT CAPACITY									
HEP		Naphtha	Dual Train Combined-Cycle	Baseload	60.0	1999	On	58.0	0.0
PGV		Geothermal	Geothermal steam	Baseload	30.0	1986	On	21.4	0.0
TOTAL FIRM CONTRACT CAPACITY					90.0				
TOTAL FIRM GENERATING CAPABILITY					276.1				
AS-AVAILABLE GENERATION									
HRD			Wind Turbine	As-avail	10.6	2006	Off	0.0	0.0
Wailuku River			Run-of-river hydro	As-avail	12.1	1993	On	1.8	0.0
Lalamilo wind			Wind Turbine	As-avail	2.3	1986	Off	0.0	0.0
Puueo Hydro No. 1			Run-of-river hydro	As-avail	2.5	2005	On	2.4	0.0
Puueo Hydro No. 2			Run-of-river hydro	As-avail	0.5	1918	On	0.3	0.0
Waiiau Hydro No. 1			Run-of-river hydro	As-avail	0.8	1921	On	0.7	0.0
Waiiau Hydro No. 2			Run-of-river hydro	As-avail	0.4	1928	On	0.4	0.0
					29.0				
Total Generation Capacity, Output and Reserve					305			125.7	10.3

2.3 Sequence of Events

2.3.1 Sequence of Events Review

We have reviewed the sequence of events from just before the earthquake to the outage as developed in the Hawaii Electric Light Company, Inc. October 15, 2006 Earthquake Incident Report, March 14, 2007.

This report was reviewed against information from the EMS, supervisory control and data acquisition (SCADA) reports, and relay event reports. This sequence of events coincides with the information displayed in the following figures. Figure 1 shows the system generation and frequency on the HELCO system from the time of the earthquake until 0800 hours when the frequency stabilized. Figures 2 shows the megawatt output of the separate generating units and the system frequency, with the timing of significant events, from 07:07:00 to 07:21:00 to provide an expanded view of the generator operation events.

The EMS, SCADA, and relays are continuously synchronized to the same clock so time stamps correlate between devices. Time stamps for the sequence of events determined below are primarily derived from the EMS and SCADA reports which are recorded in two second intervals. All times used in this report are based on the 2400 hour time clock.

System Load and System Frequency
October 15, 2006 Earthquake

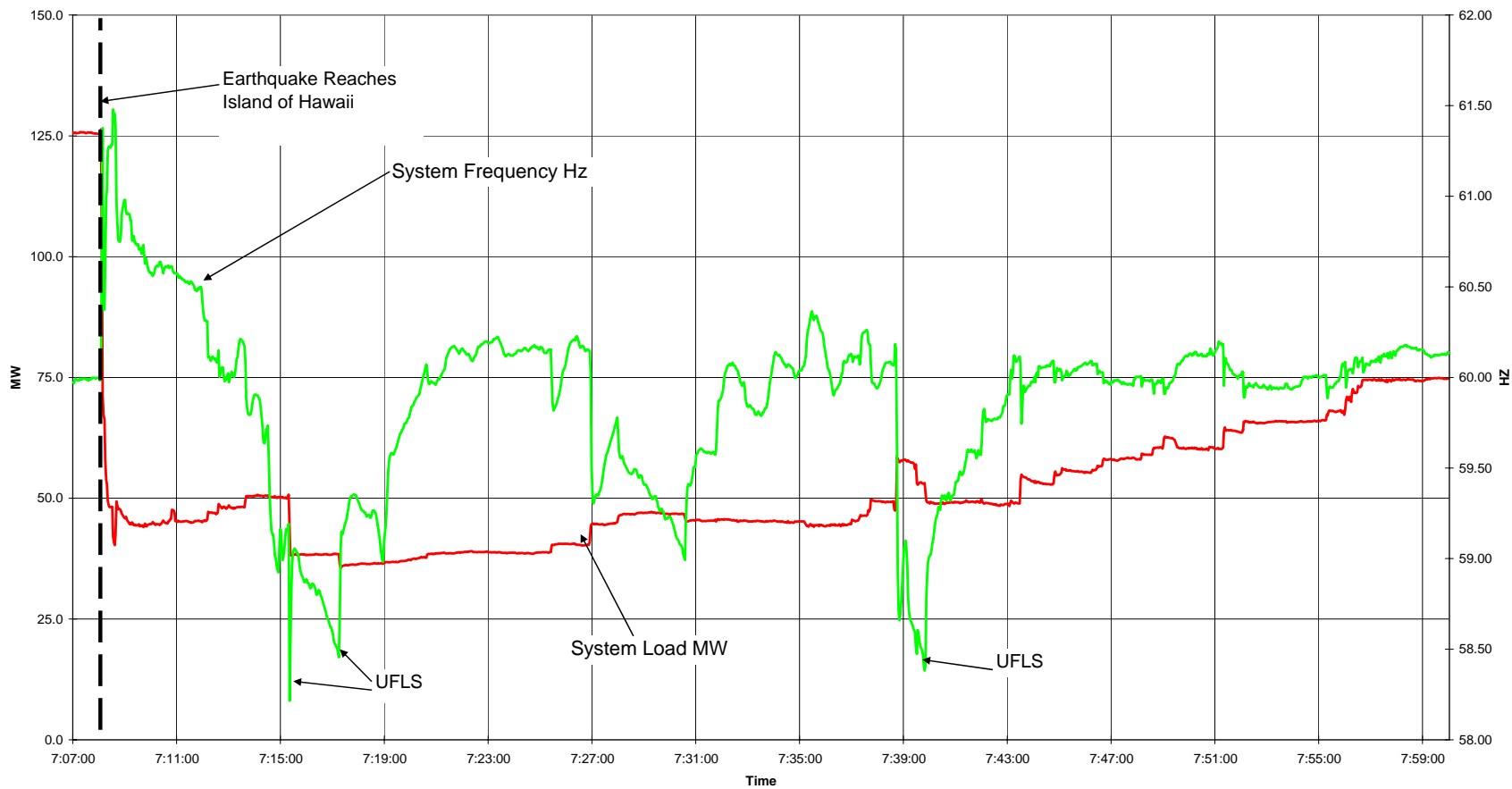


Figure 1: System Load versus Frequency Timeline October 15th, 2006

Unit Load and System Frequency
October 15, 2006 Earthquake

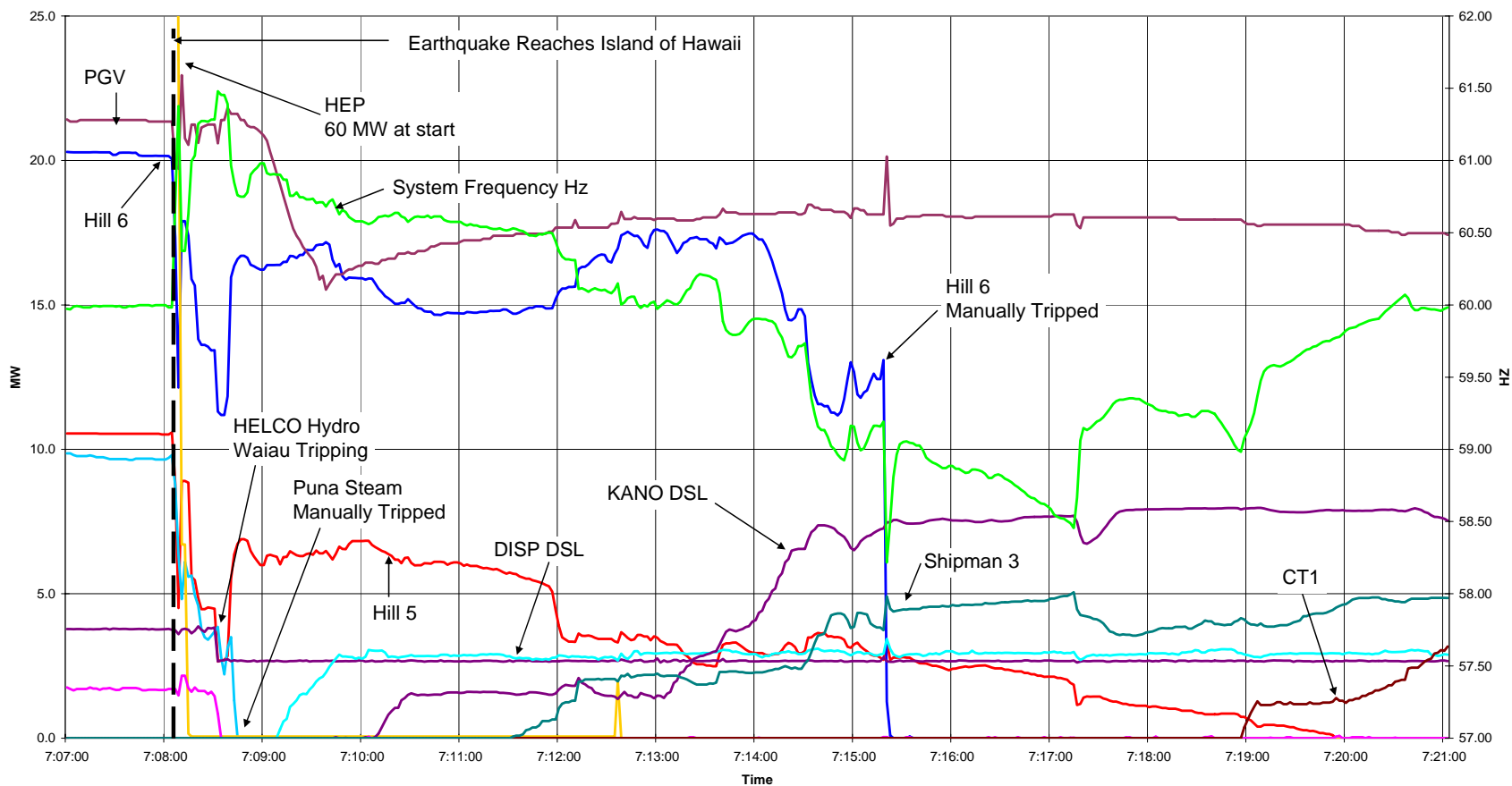


Figure 2: Individual Generator Output Timeline - October 15, 2006, 07:07:00 to 07:21:00

Summary of the System Dynamics

At the onset of the earthquake, the system was operating normally with all transmission lines in service and generation properly dispatched to provide sufficient regulating reserve in accordance with the HELCO operating practices. There were essentially three areas of events from the time the earthquake hit until the generation “island” on the east side of Hawaii stabilized.

PHASE 1 - 07:08:02 to 07:08:32 hours

During the first 30 seconds of the event:

- 19 of 28 transmission circuits tripped open or were de-energized due to faults and relay operations,
- 11 of 20 69 kV switching stations were de-energized,
- 3 of 5 34 kV Sub-transmission lines tripped open,
- 77 of 124 distribution circuits were de-energized,
- Hamakua Energy Partner (HEP) CTs tripped off line due to vibration.

Trips of the transmission circuits blacked out the system from Pepeekeo around the north and down the west side of the island to Kealia. The initial loss of load resulted in over frequency with generation exceeding load on the east side of Hawaii. The Hill 5, Hill 6, PGV and Puna units reduced output to match generation with load as indicated in Figure 2. Waiau and Wailuku hydros tripped off-line.

PHASE 2 - 07:08:32 to 08:00:00 hours

Line 6500 Kaumana to Pohoiki tripped and then automatically reclosed which added to the disturbance on the grid remaining on the east side of the island. As the HELCO steam generation quickly ramped down to match the load lost on the west side of Hawaii when transmission circuits tripped, the Puna steam unit began to motor and was tripped by the operator. The Hill 5

boiler tripped and the generator began to reduce power output as the steam pressure declined. The System Operator noted that the system had separated and that the remaining generation was going through a transient condition trying to maintain generation-load match. At this point the System Operator started the standby diesel generators and Kanoelehua CT1. Shipman 3 was requested to go online. At 07:12:05, the System Operator began to systematically close transmission circuits by SCADA that had tripped to restore the 69 kV grid with the priority to reconnect the power plants. About 0714 hours, Hill 6 was producing about 17 MW when it developed a leak in the turbine steam chest and began to lose power. At this time the frequency began to decay below 60 Hz as the other units began to ramp up to absorb the reduction in power from Hill 6. Hill 6 was tripped by the operator as it was presenting a severe safety risk. Frequency then declined quickly and load shed blocks began to operate between 07:14:49 and 07:18:53 which arrested the frequency decay and increased the frequency to above 59 Hz. At about 0719 hours CT1 was connected to the bus and began to pick up load which quickly restored the frequency to 60 Hz. The 69 kV transmission grid was restored to Keahole at about 0723 hours and CT4 was brought on-line at about 0743 hours. The Puna steam unit was put back on-line at about 0737 hours. Puna CT3 was brought online at about 0748 hours. As Figure 1 shows, the frequency remained low while the System Operator closed in circuits, generation was connected to the grid and load was picked up until about 0745 hours. HEP CT1 was put back online about 0755 hours. The swift actions of the System Operator, as prescribed by the HELCO operating practices, avoided a system-wide outage.

PHASE 3 – 0800 to 2400 hours

In this phase the remaining portions of the system were assessed for damage and restored to service where possible. The System Operator had restored as much of the system as possible by SCADA. At this point the general actions were:

- HELCO Transmission and Distribution (T&D) and Production Supervisors reported to the KOCC
- Field personnel were called out
- HELCO's Civil Defense Liaison reported to the county Emergency Operation Center
- Aerial inspections were coordinated
- Priorities were established for restoration
 - Line 7300 at Ouli Substation
 - Keahole CT-5 generator step-up transformer
 - Honokaa Switching Station (opened due to customer reports of a fire)
 - Reset lockout relays

Dispatch Center

Interviews with the System Operator indicated that when the initial shaking took place, he was immediately aware that it was an earthquake. He reported that SCADA alarms went off continuously and the alarms were too numerous to list. He executed fast start of the standby diesel units and Kanoelehua CT1, and called for Shipman 3 to come on-line. Standard HELCO procedure for a major system upset is to get as much generation ready to come on-line as possible. When Puna Steam, Hill 5 and Hill 6 were taken off-line, automatic load shedding operated and was sufficient to help stabilize the system frequency. The additional generation from the diesel units, Kanoelehua CT1 and Shipman 3 helped to make up for the lost capacity and restored the system frequency to 60 Hz. Manual load shedding was not required.

After the shaking stopped and the system stabilized with a generation island in the east Hawaii area, the System Operator began to close back in transmission lines with SCADA. Additional supervisory and operations staff began to arrive at the KOCC on their own as they recognized that an earthquake had occurred. At that time one System Operator managed the generation while the

second used SCADA to open distribution breakers on transmission lines that had tripped open and were de-energized. This allowed test reclosing of transmission lines without addition of load. HELCO's general practice is to test reclose a line that has tripped to determine whether a fault condition remains or if it has cleared. This practice significantly reduces the duration of outages following momentary faults. As generation and load restoration progressed, under frequency load shed circuits were restored as a precaution in case of other low frequency events.

HELCO's internal microwave and land line communications systems for the SCADA and hotline to power facilities and police/fire dispatch remained in service along with base-to-mobile radios and cell phones. The land line telephone system and cell phone system experienced some congestion, but were not significantly hampered. Paging/text messaging via the company email system stopped working shortly after the first message was transmitted and received.

Power Plants

The power plants experienced significant load swings as the transmission system separated the east side generation from load on the west side of the island.

As a result of the over-frequency condition in east Hawaii, resulting from the loss of transmission lines, Puna Steam Plant Unit output ran back down eventually to zero. As the unit began to motor the control operator tripped the unit off-line as they had been previously trained. The unit experienced an event in 2005 where the generator motored for a significant period of time and as a result, operators received subsequent training regarding protective actions under this circumstance. Operators maintained boiler pressure so that they were able to quickly bring the Puna unit back on-line when the system stabilized.

Hill 5 experienced a boiler trip (specific cause is uncertain) and had difficulty purging the boiler for a re-start. The purge problem prevented re-firing the boiler before boiler pressure declined to the point where the unit had to be tripped. After resolving the boiler purge problem, the operators had trouble with a fuel oil trip reset, which when corrected allowed the boiler to be fired and the unit brought on-line at about 0817 hours.

Hill 6 operators noted that this unit is known to have some level indicators on the deaerator that are subject to false trip during physical shaking. During the earthquake these level indicators tripped the boiler feed pumps which did not automatically re-start. The operators were aware that these could falsely operate during an earthquake and quickly restarted the boiler feed pumps manually. As the unit was stabilizing, the turbine chest developed a severe superheated steam leak which caused severe safety concerns due to the high pressure steam flowing into the turbine operation deck. The unit was tripped at this time and was not returned to service until repairs were completed on October 18th.

The Keahole operation room had some cosmetic damage but remained in operational condition. Initially, Keahole was in the black portion of the grid and could not start or connect any units until the 69 kV transmission grid was restored to the station.

IPPs

The HEP Distributed Controls System (DCS) was inundated with alarms and the operators couldn't keep up with them. The quake triggered vibration sensors which tripped the combustion turbine units, which in turn tripped the combined-cycle steam turbine. The personnel reported some minor damage to the control room (books fell off shelves and ceiling tiles fell down). After inspection they found a breeched water line to the de-mineralizer and minor damage to cable trays. When the CTs tripped, the operators started their plant diesel generator and initiated a high

speed crank to prevent thermal lock. The transmission system to Haina was restored within five minutes after the earthquake and HEP CT1 was reconnected to the grid at 0755 hours. During the restoration, HEP CT1 tripped due to a cable that had loosened on the aft accelerometer and this trip resulted in underfrequency load shed on the HELCO system at 1009 hours.

Outages of the 7300 and 8800 69 kV transmission lines restricted the output of HEP to about 45 MW to avoid overloading the 7200 69 kV transmission line.

HEP staff indicated that they were able to maintain communication with HELCO and that the coordination was good throughout the event and restoration.

PGV remained online throughout the earthquake and the associated system frequency excursion. Some output was reduced for a period when plant auxiliaries were tripped due to the low frequency. PGV was able to restore generation output to the pre-event level by 0800 hours.

Transmission and Distribution System

The EMS and SCADA indicated automatic Under Frequency Load Shedding (UFLS) scheme activation as designed. The transmission system remained primarily structurally intact. For many of the 69 kV and 34 kV circuits that tripped, the System Operator systematically reclosed circuits through the remote capability of the SCADA immediately after the generation islanded with load on the east side of Hawaii and was stabilized.

2.3.2 System Restoration

The following information is based on interviews with management, the System Operators, and power plant operators, as well as information that were gathered from various sources including the EMS and SCADA.

Key management and supervisory personnel voluntarily responded after the earthquake. Within a few minutes after the earthquake, supervisory staff came into the KOCC to supervise and support the system stabilization. One of the Shift Supervisors was on-site to assist, followed shortly by one of the Assistant Superintendents. They brought in an additional System Operator and supervised the system restoration and set priorities. Within a half an hour, there was a supervisor assisting at Keahole Power Plant, Puna plant, and Hill plant in addition to two supervisors who assisted as necessary at various plants and system operations. The second Assistant Superintendent arrived approximately 40 minutes after the earthquake. As additional supervisory personnel arrived, some remained at System Operations to assist with system recovery and others were sent to the various plants to direct startup (where applicable) and direct assessment surveys. Even though activation of the Incident Management Team was not deemed necessary, several key position activities were performed by the assigned individuals as they arrived and assisted in restoration.

The HELCO senior staff assessed the system and called in trouble inspectors and construction and maintenance (C&M) staff to inspect the system and begin repairs. The staff from the Kona and Waimea baseyards were assigned to assess the condition of local substations and lines and prepare them for re-energization. Additional HELCO staff were mobilized from the eastern side

of the island to travel to the west side to assist with reenergizing the substations and transformers.

Restoration activities were hampered by road closures as shown in Figure 3.

The primary objectives of the overall restoration were:

- 1) Stabilize the system by bringing generation and load in balance;
- 2) Make generation available through restart of the steam plants and by re-establishing the transmission system connections to that portion of the island that was separated. The route taken for transmission restoration was designed to restore generating facilities then add circuits as needed to rebuild the transmission system;
- 3) Restore underfrequency circuits;
- 4) Communicate to T&D field personnel regarding lockouts or other problems that required field personnel to resolve; and
- 5) Complete restoration of customers as generation was made available and as the transmission/distribution system repairs were completed.

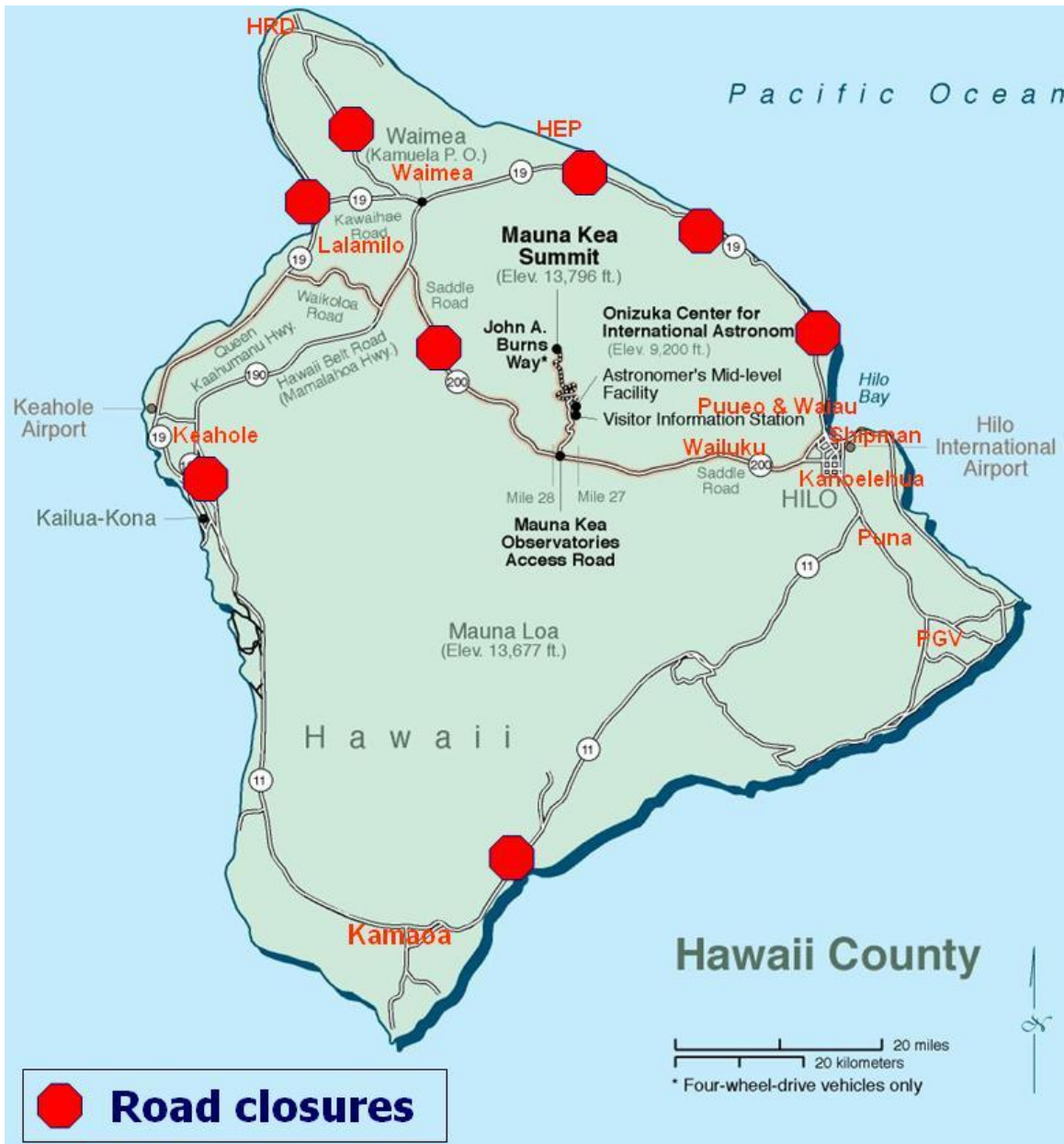


Figure 3: Initial Hawaii Road Closures Due to the Earthquake

System Restoration

The 69 kV grid was restored to Keahole power plant by 0730 hours and CT-4 came on-line about 0742 hours. By 0802 the System Operator had closed in all forty five (45) breakers that could be remotely closed by SCADA control. T&D personnel responded and inspection of the system found the following:

- Ten (10) spans on 3200 line (34 kV transmission line from Honokaa serving Paauilo substation) failed
- Insulator on 3300 line (34 kV transmission line from Waimea serving North Kohala) failed
- Transmission switches at Honokaa Substation out of alignment and arcing
- Four (4) substations had potential transformer secondary disconnect switches damaged
- Fifteen (15) substations had primary transformer fuses shaken off the fuse holders
- Capacitor bank and 69kV bus connectors at Ouli Switching Station damaged, that disabled four 4.8 MVAR shunt capacitor banks
- Eight (8) transformers (substation and generator step-up) had lockout relays (designated 86T) which tripped and locked out by operation of sudden pressure sensors due to the shaking of transformers by the earthquake
- Kahaluu bus differential relay operated.
- Others
 - No power – Honokaa Hospital
 - Structure fire – Puu Nani Drive
 - Power problem – Kona Community Hospital
 - Numerous service line (s/l) problems
 - Honomu Ln – Lightning arrester fell off pole
 - Customer primary service – lines hanging from arresters

The generation available during the initial stage of system stabilization until about 0800 hours was:

- Shipman 3
- Puna Steam
- Kanoelehua Diesel Generators
- CT-1 (Kanoelehua), CT-3 (Puna) and CT-4 (Keahole)

- Puna Geothermal Ventures (PGV)
- Puueo Hydro
- Dispersed Generators at Panaewa, Punaluu and Kapua
- HEP CT-1

Restoration of HEP generation and the Keahole CT-5 were high priorities for the System Operator to avoid a generation shortfall. The transmission grid to HEP was restored by 0713 hours and to Keahole about 0723 hours. Keahole CT-4 came on-line about 0743 hours followed by HEP CT-1 at 0755 hours. The HEP Steam Turbine Generator (STG) was brought online at 0919 hours. The trip of HEP CT-1 generator and STG at 1009 hours caused system under frequency and trip of four UFLS circuits. HEP CT-2 was back online at 1034 hours, followed by the heat recovery steam generator at 1109 hours. Keahole CT-5 came online at 1451 hours after field personnel reset the step up transformer lock-out relays.

Substation and power plant transformers that tripped and locked out (86T) via the transformer sudden pressure protective scheme were visually inspected for physical damage resulting from the earthquake. When no damage was noted the decision was made to reset the sudden pressure lockout relays and perform a test reclose on the breakers that connected the respective transformers while monitoring existing metering and protective relays to check for internal faults. The first transformer energized was the Keahole Diesel Generator transformer at about 0847 hours. When this transformer did not show signs of an internal fault, additional units that had tripped on sudden pressure had their respective 86T lockouts reset and were re-energized.

Lines 7300 and 8300 had tripped open at Ouli Switching Station during the earthquake and failed to close when ordered to close by SCADA. Damaged equipment was subsequently found at Ouli. At 1219 hours, equipment arcing at Honokaa Switching Station led to a forced outage of Line

8800, which routed all HEP power through Line 7200 to the West Hawaii area. The full HEP rated output would exceed the line's emergency rating of 300 amps, and HEP was curtailed to 45 MW to avoid damaging Line 7200.

Transmission lines 7300 and 8300 were restored at 1414 hours after repairs to the air switches were made at Ouli Switching Station. The restoration of the 69 kV transmission system was returned to normal configuration at 1716 hours after transmission line 8800 was restored. Line 3300 (servicing North Kohala) was taken out of service at 1652 hours to repair an insulator that was damaged by the earthquake; it was restored at 1854 hours.

Figure 4 shows the load curve for October 15th in comparison to load on Sunday October 8th. The curve profiles for October 8 and 15 are similar prior to 0707 hrs and after 1800 hrs. Firm capacity and firm capacity with as-available generation are also shown on the graph, to illustrate the reserve margin that is typically available.

LOAD PROFILE

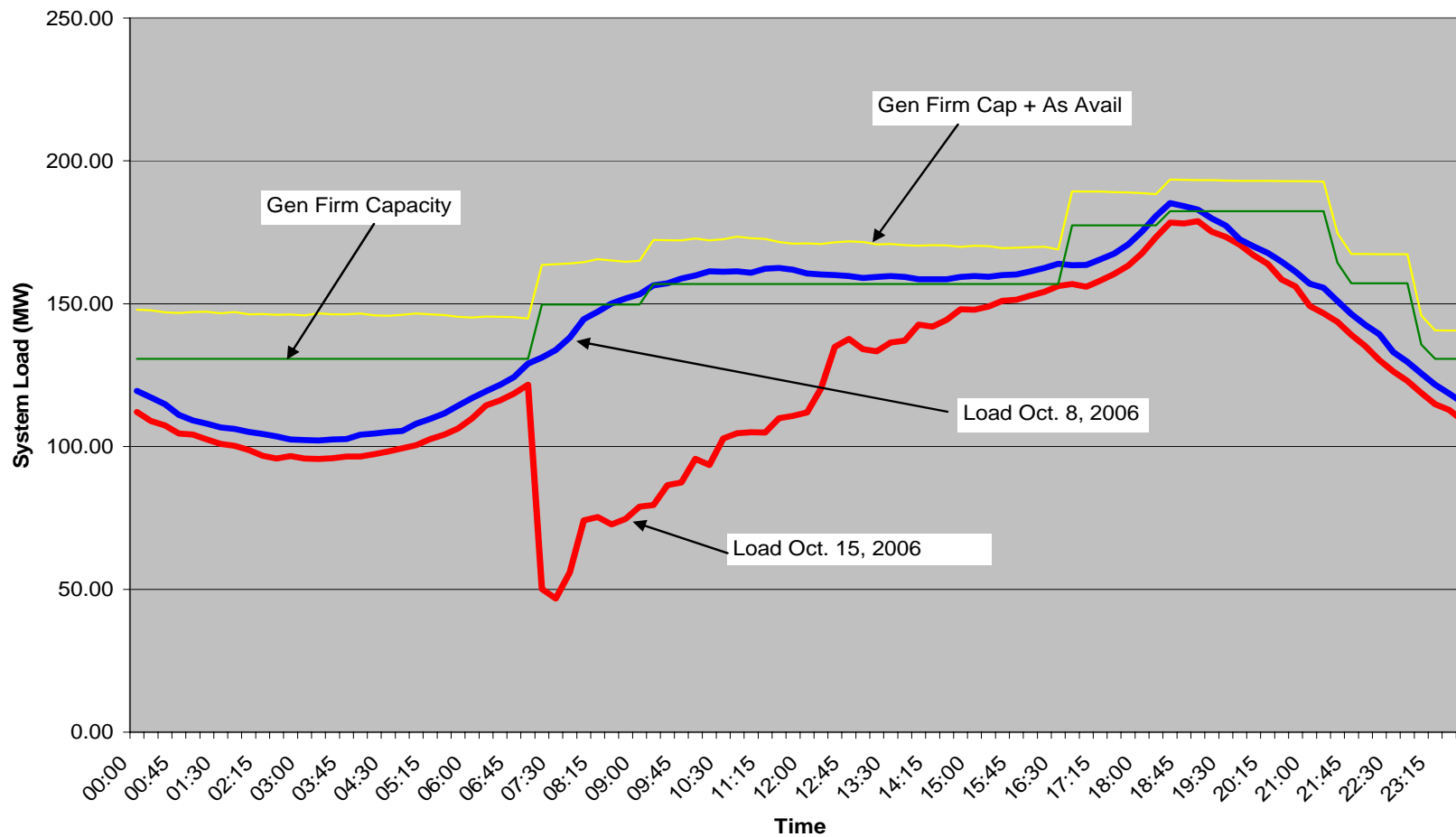


Figure 4: October 15, 2006 Generation Compared to Previous Sunday Load Curve

3 Evaluation

3.1 Generation Capacity

3.1.1 HELCO Generating Fleet

Approximately 276 MW of firm generating capacity is currently installed on the island of Hawaii, with a further 29 MW of wind and hydro power as-available. Of the 276 MW, 186 MW is owned and operated by HELCO and 90 MW by Independent Power Producers (IPPs). The HELCO and IPP plant capacities are summarized in Table 1.

The HELCO generating equipment is notable for:

- 64% of the base load capacity is owned by two IPPs and comprises a combined cycle combustion turbine plant with a heat recovery steam turbine and a geothermal plant. The remainder of the base load capacity comprises steam plant installed between 1965 and 1974.
- The remainder of the load is supplied with combustion turbines in open cycle mode, steam turbines installed in the 1950s, and 15 relatively small reciprocating engines for peaking installed between 1962 and 1998.

Expected Performance of Generating Plant During Major System Disturbances

No reciprocating engine plants were operating at the time of the earthquake because the reciprocating engine plants are used for peaking and emergency, rather than base load.

Steam plants can be very valuable in providing frequency stability. However, older designs at HELCO may have difficulty remaining in service following sudden, large load swings, depending on the boiler ratings. Sudden large load pickup and reduction can take boiler operating parameters, such as drum levels, to the point where control equipment intervenes to protect the plant from damage and automatically trips the unit out of service. Once the boiler trips, getting a purge of the boiler fuel fumes and re-light, while keeping the turbine generating, requires a lot of skill. In HELCO's case, the operators report that they are successful in relighting the fires and keeping the turbine on-line at least 2/3rd of the time, and they continuously work to improve this ability. When a plant is suddenly tripped off-line, there are numerous steps required to secure the plant, assess equipment conditions, and proceed through the startup sequence. To complete these sequences requires between 20 minutes and 4 hours depending on the residual steam pressure/temperature of the boiler.

Combustion turbine plants of the type installed at HELCO and HEP are able to respond well to rapidly changing loads and can be brought on-line relatively quickly. The turbines are manufactured by General Electric, type LM2500. The LM2500 is based on an aero engine that has been modified for use as a land-based generating set. It is typically used, as in this case, in combined cycle mode whereby the heat in the turbine's exhaust gas is used to generate steam for a steam turbine. HEP uses two combustion turbines feeding heat to one steam turbine – again a typical and proven arrangement for a cost effective and efficient installation. The associated HEP steam turbine, which uses steam generated from the exhaust gas heat of the combustion turbines, will take longer to be brought on-line and is less able to accept significant load changes.

However, the combustion turbines can operate in “open-cycle” mode, i.e. without the steam turbines running, to serve load until sufficient exhaust gas heat is available to bring the steam turbines on-line. The HELCO CTs are run in simple cycle mode.

3.1.2 Operational Generating Capacity on October 15

The generating capacity in operation immediately before the earthquake was approximately 136 MW, and the system load was 126 MW. HELCO was running all three of its designated base load steam plants, taking output from HEP and PGV, and a small amount of hydro power. Anticipating morning load increases, Shipman 3 was in the process of steaming up and preparing to go on-line at the time the earthquake struck.

The following generators were in operation at the time of the earthquake:

Hill Generating Station

Hill 5 - Steam turbine, capacity 14.1 MW, load at time of earthquake 10.5 MW

Hill 6 - Steam turbine, capacity 21.4 MW, load at time of earthquake 20.3 MW

Puna Generating Station

Puna Steam turbine, capacity 15.5 MW, load at time of earthquake 9.9 MW

IPPs

HEP - Combustion turbine/steam turbine, capacity 60 MW, load at time of earthquake 58.0 MW

PGV - Geothermal station, capacity 30 MW, load at time of earthquake 21.4 MW

Wailuku River Hydro, capacity 12.1 MW, load at time of earthquake 1.8 MW

Puueo Hydro, capacity 3 MW, load at time of earthquake 2.7 MW

Waiau Hydro, capacity 1.2 MW, load at time of earthquake 1.1 MW.

3.2 Earthquake Events Analysis

3.2.1 System Operations Event Response

After the initial tremor, it was clear to the System Operator that the system had experienced an earthquake. By the time the earthquake (reported to be 15 to 20 seconds by the Hawaii Volcano Observatory), 19 transmission lines, substation transformers and the HEP combustion turbines had been tripped by their protective relays. The west Hawaii HELCO system from Kealia to Pepeekeo was blacked out. The System Operator reported that the SCADA alarms screen was scrolling too fast to comprehend, so he focused on the system wall display to assess the state of the system.

With the separation of the transmission system, the east Hawaii area remained connected to the Puna Steam Plant, Hill 5, Hill 6, PGV and Puueo Hydro. The frequency rose to about 61.5 Hz. As Puna Steam was tripped because it was motoring and Hill 5 reduced power output due to a boiler trip, the System Operator took immediate action, as is standard practice, and fast started the diesel units, and Kanoelehua CT-1 and called for the Shipman 3 unit to be brought on-line.

The HELCO system operators have the ability, in a single operation, to send a start signal to the diesel generators, with the exception of the diesel 11. These fast start units are four dispersed 1MW diesel generator units (one each at Panaewa, Ouli, Kapua and Punaluu), three 2.75MW units at Kanoelehua, and three 2.5 MW units at Waimea and three at Keahole. The generator at

Ouli (on the west side of the island) was, as a result of the loss of transmission lines, unable to be connected, but the other three 1MW units started up and connected to the system to provide 3MW of generation, just after 07:09. These were closely followed by select Kanoelehua units a minute later. The Keahole and Waimea units were also in an area where the transmission system had de-energized, could not connect to a dead bus, and had shut down.

In anticipation of load increasing during the morning, the steam turbine at Shipman 3 had been steamed up and was ready to be brought on-line. It was brought on-line at 7:11:20. This was followed at 7:18:57 by the 11.5MW combustion turbine at Kanoelehua. These units helped to compensate for the loss of the steam turbines at Hill that came off-line at 7:15 and 7:21.

When Hill 6 tripped due to a turbine steam chest leak, the frequency quickly declined below 59 Hz and the automatic load shed scheme activated to arrest the frequency decay and bring the frequency above 59.0 Hz. The frequency again began to decline as Hill 5 power output continued to decrease and it appears additional load was shed returning the frequency to about 59.3 Hz. The frequency then declined again as the Hill 5 output continued to reduce, until CT-1 came on-line and quickly matched load to stabilize the frequency. Once the frequency stabilized, the System Operator immediately began to close back in the 69 kV transmission circuits by SCADA, and bring generation on-line to restore the system load. The transmission path was restored to Haina, Waimea, Keamuku and Keahole by 0725 hours to allow reconnect of the major generation resources. The System Operator had remotely restored the majority of the transmission system to the west side of the island by 0800 hours. Load was added in conjunction with generation as the System Operator and Plant Operators managed generation and load additions. The generation, once connected to the grid, was put on AGC when minimum load for AGC control was reached, to control loading and frequency. As the system restoration continued additional supervisory and system operations personnel reported in and began to assist with the restoration activities.

At about 1009 hours, HEP CT-1 and the steam unit tripped when the cable connection to the aft accelerometer on the CT failed. This dropped 21 MW of generation and the system again went into underfrequency and triggered load shedding. HEP CT-2 was put on-line at 1033 hours followed by the Heat Recovery Steam Generator (HRSG) steam unit at 11:09 hours and HEP CT-1 at 1321 hours.

In cases such as the Keahole diesels and CT-5, the units' associated generator step-up transformers tripped on the activation of a transformer sudden pressure lockout relay which required an inspection of the transformer and manual reset of the lockout relay prior to re-energizing the transformer. There were also a number of cases where substation transformers had fuse elements that were shaken from their fuse holders, requiring maintenance crews to manually close them.

Overall, the separation of the transmission system dropped enough load from the west side of the island so that the east side had a generation surplus with respect to load resulting in over speed/over frequency, which caused the HELCO generators to reduce power output, and consequently the trip of Puna steam on a motoring condition and created boiler upset conditions on Hill 5 and Hill 6. The immediate actions by the System Operator to start the diesels and Kanoelehua CT-1 and to have Shipman 3 put on-line, as per HELCO operating practice, are credited with providing sufficient generation capacity, in combination with the automatic under frequency load shedding to balance generation with load and stabilize the system, preventing an island-wide blackout. The System Operator's actions to immediately begin test closing the 69 kV transmission lines, restoring circuits to HEP and the west side of the island, also per HELCO practice, significantly reduced the outage time for a large portion of HELCO's customers.

3.2.2 Transmission and Load Restoration

HELCO T&D staff were dispatched to inspect the transmission lines and substations and prepare them for restoration where the System Operator indicated that he could not operate the remote controlled devices by SCADA. As the inspection and restoration progressed, the earthquake-caused damages listed in Section 2.3.2 were noted and assessed, and repairs were initiated.

Ouli Switching Station was found to have equipment damage including the following: 8 of 12 capacitor bank VBM style single phase switches were damaged; capacitor bank potential transformer leads had pulled free; the station service transformer had moved and tore loose from its anchors (failed several days later); and a bus PT lead pulled free which would make the line relays non-directional. The transformer sudden pressure relay had operated and locked open the transformer breaker. Isolation and repair of damaged equipment delayed re-energization of transmission lines 7300 and 8300 until about 1414 hours.

Honokaa Substation was reenergized at about 0712 hours. Transmission line 8300 from Honokaa to Haina was tripped open by the System Operator at about 1220 hours when a customer reported a fire in the substation and line crews determined that transmission line 8800 air switch had been knocked out of alignment and was arcing across its contacts.

With transmission lines 7300 and 8800 out of service, HEP was left connected to a radial system transferring its output across Line 7200. Line 7200 is constructed with 2/0 ACSR cable and would overload with the full output from HEP. This concern became a priority for System

Operations and, consequently, HEP output was curtailed to 45 MW until the damage was isolated at Ouli Substation and Lines 7300 and 8800 were restored to service.

Substations that could not be restored by SCADA and required manual assessment for damage were located in the west Hawaii portion of the system and maintenance crews from Hilo were dispatched to assist. These crews were somewhat delayed awaiting road closures to be cleared. The crews assessed equipment condition, reset lockout relays and closed transformer fuses to allow the System Operator to close in load as generation became available. Of the 62,000 customers on the HELCO system effected by the outage, 61,000 had power restored by 1500 hours. The remaining customers had power restored by 2300 hours as distribution line repairs were completed. The following sections evaluate the generator, line and transformer trips.

3.2.3 Generator Trips

Summary of generator trips.

7:08:12 HEP station tripped on high vibration.

7:08:32 Waiiau hydro units tripped.

7:09:18 Puna steam turbine was found to be motoring, was tripped offline and kept in readiness to reconnect as soon as possible.

7:15:17 Hill 6 steam turbine showed a deaerator level alarm though this was not a trip condition. But then the turbine developed a steam leak in the turbine chest seal and had to be manually taken off-line.

7:21:19 Hill 5 steam turbine tripped following the trip of the boiler due to a low boiler drum level. The unit had problems with the purge process, lost steam pressure and was tripped.

Puna Power Plant

The generating plant at Puna is part of a decommissioned sugar cane processing plant and was purchased by HELCO when the sugar plant was no longer viable. The boiler was originally sized to feed steam to the turbine and to parts of the sugar refining process, and is approximately twice the size needed to power the steam turbine alone. This means that the boiler can cope very well with sudden load changes.

Tripping of transmission lines to the west side of Hawaii resulted in a surplus of generation on the east side of the island. Consequently, the system frequency increased on the east side and the Puna steam turbine valves closed to try to decrease the speed of the machine. The machine was effectively being motored by the system and the unit is not presently equipped with a reverse power relay to automatically trip for this condition. Motoring a generator can lead to serious problems, and the established operating procedure correctly requires that the unit be tripped under this condition. In 2005, the unit had motored for a prolonged period before being tripped offline. The Puna operators had been provided specific training regarding this possible event and the expected actions to trip the plant and prepare to come back on-line. The Puna operators followed these procedures, tripped the plant, and readied it to come back online when the frequency stabilized.

Hill Power Plant

The steam turbines at Hill, Hill 5 and Hill 6, both came off-line during the disturbance for different reasons.

Hill 6 came off-line first. Initially its boiler indicated a deaerator level alarm, though this is believed not to have been caused by a genuine deaerator level problem but instead by the action of the earthquake's vibrations on the liquid level switch monitoring the level. The shaking of the

HEP Power Plant

High vibration caused the two combustion turbines at HEP Generating Station to trip just after 0708 hours. These generator sets are equipped with vibration sensing devices which detect the relative positions of shafts and housings to determine if vibration is occurring which the manufacturer considers could damage the machine. Both the combustion turbine itself and the electrical generator have vibration sensing, and it was the vibration sensing on the generators, (Bentley Nevada 3300) rather than the turbines, that caused the CT's to trip. The HEP CT's both dropped to minimum load as the system frequency increased to above 63 Hz when the transmission system tripped. Then the CTs tripped on vibration about seven seconds after the earthquake began. The steam unit then tripped on logic that shuts it down if no CTs are operating. The operators immediately started the diesel generator and put the turbines on high speed turning gear to prevent thermal lock.

LM2500 Combustion Turbine Monitoring

When used in a power generation application, LM2500 combustion turbine-generator sets, such as the HELCO and HEP sets, are equipped with vibration sensing equipment on both the turbine and generator as follows:

Accelerometers – the combustion turbine is fitted with two accelerometers, one on the gas generator at the air inlet end, the other on the power turbine. These sensors detect vibrations in the combustion turbine casing. The aim is to detect vibrations at normal shaft speeds to provide an alert if a shaft becomes unbalanced. The LM2500 has high background noise (vibration) levels, so a speed signal is taken from each shaft (gas generator shaft and power turbine shaft) in order to filter out vibrations which do not occur at shaft speeds. Alarm and trip levels are set for each accelerometer for vibrations at each shaft speed. Thus, the accelerometers on the combustion turbines are not designed to detect vibrations due to external forces, only vibrations at much

higher frequencies due to shaft unbalance problems. In common with most aero-derived combustion turbines it is fitted with rolling element bearings which are resistant to externally applied vibrations.

Proximity probes – the electric generator, which is a separately manufactured component from the LM2500, is fitted with proximity probes which detect the distance between the bearing housings and the shaft. There are four probes, two at each machine bearing (i.e. at each end of the generator). Each pair of probes is arranged at 90°, one in a vertical orientation and one horizontal. The purpose of these probes is to detect relative lateral movement between the generator stationary and rotating parts, which will occur in the event of bearing or lubrication failure, shaft unbalance or other types of internal damage. In fact, these are not truly vibration sensors at all, but are, as the name says, proximity detectors. Proximity detectors are used because the bearings in the generator sets are plain journal bearings which rely on a hydrodynamic film of oil for lubrication, as is the case with generators of this size world-wide. Significant vibration from any source and at any frequency can cause the film of oil to be disrupted which would lead to bearing failure and possible shaft damage. The proximity probes detect changes in shaft/housing clearances which may indicate loss of oil film lubrication. When the earthquake struck, the proximity probes on the bearings of the generators of combustion turbines HEP CT-1 and CT-2 detected movement between the bearing housings and the shafts in excess of the “trip” threshold and caused the machines to shut down.

3.2.4 Transmission Line Trips

Inspection and assessment by the T&D staff during and subsequent to the restoration indicate that relays on 12 of the 69 kV lines that tripped recorded a direct trip (DT), with no other fault sensing relay initiating the trip. After some investigation, it appears that an auxiliary relay contact momentarily closed, attributed to the earthquake shaking, to direct trip the transmission circuits. These relays are an ABB Style AR auxiliary relay. These auxiliary relays are commonly used in the electric utility industry to provide additional contacts from one relay to other protection and control schemes. The HELCO AR relays are typically mounted on the back of the relay panel, as shown in Figure 5, or on swing panels located on the rear of the main relay and control panel.



Figure 5: Transmission line AR relay.

These auxiliary relays do not result in a lockout condition so the lines were able to be remotely closed through the SCADA by the System Operator by 0800 hours. While these relays mis-operated, the inadvertent operation resulted in disconnecting load on the west side of Hawaii which helped to offset the loss of the HEP combined cycle units and Hill 6, as indicated in section 3.2.3 above. Relays on transmission lines 7300, 7700, 8600 and 6500 indicated that they had tripped due to phase-to-phase faults, most likely due to phase wire contacts due to the earthquake shaking. These trips are evaluated to be correct operations.

3.2.5 Substation Transformer Lockout 86T Trips and Fuses

Inspection by the T&D staff during and subsequent to the restoration indicates that relays on 8 substation distribution and generator step up transformers tripped on the 86T lockout relay by the Sudden Pressure protection scheme. This relay circuit includes a Sudden Pressure sensor in the transformer that detects a rapid pressure rise inside the transformer and an external target relay to provide an indication that the sudden pressure sensor operated. Rapid pressure rise inside a transformer is typically associated with an internal transformer fault arcing and quickly causing gasses to form, which increases the pressure inside the tank. Severe overpressure can rupture a pressure release mechanism or even the tank. Since this type of fault is always permanent, the sudden pressure relay circuit activates the 86T lockout device, which must be hand reset before the transformer can be re-energized. The typical industry procedure is to perform a visual inspection and disconnect the transformer to perform integrity tests before re-energizing. This process typically would take one to two days per transformer.

HELCO T&D staff noted that 8 transformers had the 86T operate and lock out, had similar sensors and target relays. These sensors are a Qualitrol Fault Pressure sensor as shown in Figure 6 with a magnetic target relay as shown in Figure 7.



Figure 6: Transformer Fault Pressure Sensor Qualitrol.



Figure 7: Transformer Fault Pressure Target Relay and 86T Lockout Relay

Other transformers on the system were noted to have a Qualitrol fault pressure sensors and solid state target relays. These units did not trip during the event.

The transformers were visually inspected and no indication of an overpressure condition was noted, such as rupture of a pressure release disk or setting of the pressure release flag. Once the coincidence on equipment was noted, HELCO staff test closed on the Keahole diesel generator transformer while monitoring the existing metering and protective relaying. Since Hawaii is remote from transformer repair facilities, they determined that an internal fault would most likely require replacement of the transformer rather than shipping the unit to a repair facility. Thus, there was little risk that re-energizing a faulted transformer, and increasing internal damage would extend the outage time if a replacement would be required anyway. When this transformer did not show any sign of a fault, they then continued to reset the other substation transformer 86T lockout relays and re-energize the transformer while monitoring the metering and relaying for signs of an internal fault. At this time, it has not been determined whether the miss-operation was due to the sensor or the target relay. It is possible that the sensor construction allowed the seismic acceleration of the oil to trigger the device or that the target relay closed its contact due to seismic shaking.

Fifteen substations had primary fuses shaken open from the fuse holders during the earthquake. These stations required that a maintenance crew member drive to the substation and manually close the fuse.

3.2.6 Communications

HELCO has several internal communication systems with redundant paths. These consist of Digital Microwave and Fiber, UHF/VHF radio, hotline between system operations and the power plants, email and cell phones/pagers for key personnel. All personnel within HELCO and at the HEP power plant indicated that the communications systems worked well throughout the event. The one system that stopped working is the email server that allows text messaging to cell phones and alpha-pagers for key personnel. For this system, the shift clerk dispatcher prepares an email message, keys it in and it is sent to personnel with pagers. Information typically sent includes system status, known problems, and directions for field personnel. In HELCO's case, all email and intranet traffic is routed through HECO. Only HELCO's first text message following the earthquake was routed through properly. When the Maui and Oahu systems lost power, no text messages and alpha-pages could be sent. On October 15th, loss of the paging/text messaging communication system did not hinder or delay HELCO's ability to respond to the partial outage and efforts to restore the system.

4 Conclusions

After evaluating general system information provided by HELCO, the data logs and other automatically generated information and information discussed throughout this report, along with the statements of the operators on duty during the event and restoration, we conclude:

1. The main underlying cause of the partial system outage was the earthquake inducing the operation of relays during the seismic shaking of transmission line ABB Style AR auxiliary relays; and Qualitrol Fault Pressure sensors with electro-magnetic target relays. This led to an outage of the transmission system from north of Kealia in South Kona to Pepeekeo on the Hamakua coast. The earthquake also initiated the trips of HEP on vibration. The loss of load on the east side of the island from the transmission system separation initially resulted in over frequency on the remaining portion of the system, which then went into under frequency and load shed when Puna Steam, Hill 6 and Hill 5 went off-line. Recommendations are presented to assess and remedy these issues.
2. The manual trip of Puna Steam Unit was reasonable and in the public interest. When the system went into over-frequency, Puna Steam's governor droop response characteristic quickly caused the unit to reduce load to the point where the generator began to motor. The operator had specific training to trip the unit in this event to prevent damage that could result in extensive down time for repairs. The boiler steam pressure was preserved so that it was able to be quickly restart when the system had stabilized. No recommendation is made with regard to this operator action.

3. The trip of the Hill 5 boiler is thought to be related to the earthquake but we have not been able to positively identify a cause for the fuel oil trip. Hill 6 had earthquake caused trips of the boiler feed-water pump from liquid level switches on the deaerator level alarms, but the operators were aware of this possibility and quickly reset the pumps. The boiler feedwater trips did not result in the trip of the Hill 6 turbine. The superheated steam leak on Hill 6 is believed to have been triggered by the high pressure steam transients due to the extreme system frequencies following the loss of transmission during the earthquake. A recommendation is forthcoming to assess replacement of the liquid level switches on the deaerator level alarms.

4. The HEP combustion turbine generator vibration trips were valid to protect the units as the minimum mechanical clearances were exceeded. As noted, the unit employs proximity sensors on the generators that detect when the manufacturer's minimum mechanical tolerances are exceeded. When this occurs, the machine is in danger of sustaining damage, even if the source of the problem is external shaking. As this is concluded to be a valid trip to protect the equipment, no recommendations are forthcoming.

5. Communications internal to HELCO and with the Civil Defense agencies through the Emergency Operation Center worked very well. The microwave, VHF and UHF communication system operated properly. The only indication of a failure of the internal communication system was with the paging/text messaging system. This paging/text messaging system presently depends on equipment routed over Maui to HECO equipment on Oahu and has potential failure modes unrelated with the status of the system on the island of Hawaii. On October 15th loss of the paging/text messaging communication system did not hinder or delay HELCO's ability to respond to the partial outage and efforts to restore the system.

6. The power plants, KOCC and transmission system were properly configured, dispatched and staffed for normal operations the morning of Sunday October 15, 2006 at 0700 hours. No recommendations are made with regard to staffing.

7. The actions of the HELCO staff were reasonable and in the best interests of the public. In POWER's opinion, the HELCO personnel reacted to the circumstances in a reasonable, responsible and professional manner. The system operations and power plant staff applied training and experience in reacting immediately and properly to the changing system conditions to prevent an island-wide blackout, protect generation plant equipment, and restore power as quickly as practical. We have considered data logs of the KOCC, power plant units, and transmission system following the earthquake on the morning of October 15. We also reviewed statements of power plant operators and conducted direct interviews of HELCO personnel in various positions. We, we have not identified any instance for which we would offer an alternative action. We are not aware of any case where actions could be described as imprudent, or likely to cause injury or damage. There can be no doubt that the operating staff, especially in the KOCC and power plant, during and immediately after the earthquake at 0708 hours on October 15th, experienced conditions outside their normal operations experience. The situation was complicated and confused by the plethora of alarm indications, the transmission system tripping open, transformers tripping open, generation tripping, power stabilization of the Hilo area grid and the subsequent need to quickly restore the system. The HELCO personnel acted professionally throughout the event and restoration applying their training and experience to their assigned tasks during a distinctly extraordinary event. The system restoration plan developed by the operations staff was prioritized, reasonable and well executed. The pace of the restoration was very aggressive and well executed where the system could be remotely closed to restore the transmission to generation plants and load centers. System integrity assessment, identification of damage and repair was expedited as

much as possible, considering the staffing assignments and the initial road closures, to safely restore service to all customers as quickly as possible.

5 Recommendations

In this section of this report we provide recommendations which, if implemented, could improve the system operation under circumstances similar to those on October 15, 2006, speed up the restoration of electricity to consumers, and reduce the risk of equipment damage in the event of serious system disturbance. We recommend the following:

1. Evaluate the transmission relaying equipment, mounting methods, and operational schemes related to the employment of ABB Style AR auxiliary relays to provide relay protection schemes that are less likely to miss-operate during seismic events.
2. Investigate and evaluate the likely miss-operation of the Qualitrol Fault Pressure sensors with magnetic target relays protective equipment installed on HELCO transformers. Determine appropriate sensor/relay replacements or scheme changes that reduce the likelihood of the tripping of substation and generator step-up transformers due to miss-operation during seismic events.
3. Assess the transformer primary fuse holders to determine whether there is another model or changes to its mounting and configuration to make fuses and their holders less susceptible to shaking open during seismic events.
4. Assess application in the steam power plants of liquid level switches used in Hill 6, and determine the appropriate equipment to provide elements that are less susceptible to operation due to external shaking.

5. Assess the internal HELCO communications for paging/text messaging to determine potential failure modes and appropriate solutions.