Phase 2 Report: Oahu Wind Integration and Transmission Study (OWITS)

Hawaiian Islands Transmission Interconnection Project

Dennis Woodford
Electranix Corporation
Winnipeg, Manitoba Canada

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NREL Technical Monitor: David Corbus
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Executive Summary

The Stage 1 report for the Oahu Wind Integration and Transmission Study (OWITS) has been prepared for finalization. At the Technical Review Committee (TRC) meeting held in Honolulu January 6th and 7th, 2010, three scenarios were developed for future Study leading to Stage 2, the connection to Maui. These three scenarios are the end result of a productive evolution of ideas and study of electric power interconnection options beginning with the R.W. Beck report [1] through to developing drafts of the NREL report [2].

This present study examines the technical challenges in implementing the Stage 2 Scenarios. Essentially the islands of Molokai, Lanai, and Maui are interconnected by AC cables in Stage 2 and as such must be synchronized with each other. The major development of the Stage 2 Scenarios is the termination of the electric interconnection from Maui at Lanai and/or Molokai rather than radial at 200 MW all the way to Oahu. This avoids a long undersea cable connection all the way to Oahu and allows an AC interconnection between the islands of Molokai, Lanai and Maui.

The technical challenge in implementing the Stage 2 development based on a Stage 1 interconnection of VSC undersea cable transmission to Oahu from Molokai and Lanai is in the synchronization of the wind farms on Molokai and Lanai and the power system on Maui together with the voltage sourced converters (VSC) at Molokai and/or Lanai.

Stable synchronization is readily possible ifone of the VSC converters at Molokai and/or Lanai is operated with an independent clock that controls the frequency of the interconnected islands of Molokai, Lanai and Maui. This means the frequency of the three islands are controlled very tightly to 60 Hz. This has its advantages, but suffers from lack of DC current control in the frequency controlling VSC converter with the possibility that it might be loaded to levels of undesired DC over-current that might exceed its rating. The frequency controlling VSC converter can be a single pole cable feeder (either symmetrical monopole or one pole of a bipole) that acts without power control, not unlike a swing bus in an AC system.

To combat the possibility for DC over-current in the VSC converter that is synchronized with an independent clock, thyristor-controlled resistors will need to be applied near each VSC converter to absorb any power surges and provide time for transfer tripping or power down of the wind farms. This is to ensure the VSC transmission to Oahu that remains in service is able to remain loaded within controlled limits. In addition, certain control measures can be undertaken to assist in the prevention of DC over-currents.

When one of two VSC transmission poles or monopoles is synchronized with an independent clock and the other VSC transmission pole or monopole is synchronized with the more conventional phase locked loop (PLL) operating off the AC interconnection busbar, this operates satisfactorily. If the VSC pole with the independent clock is removed from service, the other pole with the PLL control must immediately and automatically switch to independent clock operation to maintain frequency on Molokai, Lanai and Maui.

The technical operation of the AC cable connected and synchronized Molokai, Lanai, and Maui systems and wind farms can work with the VSC transmission to Oahu providing care is taken in specifying the requirements for the VSC converter controls. The HVDC equipment suppliers will be required to demonstrate their control strategy will operate acceptably. The essential requirement of the VSC transmission control is to ensure the wind turbine generators that are applied to the wind farms will operated satisfactorily.

Acknowledgements

Appreciation is expressed for the support of Dave Corbus of NREL along with the team who met regularly to provide suggestions and directions. This includes Leon Roose, Marc Matsuura, Dora Nakafuji, Dave Burlingame, Dean Arakawa and Matt Schuerger. Appreciation is also expressed for the support from Josh Strickler of the Department of Business, Economic Development and Tourism. The concepts of the three scenarios which form the basis of this Phase 2 report were generated by the Technical Review Committee at their meeting in Honolulu January 6th and 7th, 2010. Garth Irwin of Electranix contributed important ideas towards the control of the Stage 2 system.

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Review of Stage 1

In October 2008, the State of Hawaii and the Hawaiian Electric Companies entered into the Hawaii Clean Energy Agreement to move Hawaii off of its dependence on imported fossil fuels for electricity and transportation. The U.S. Department of Energy contracted R.W. Beck in 2008 to evaluate interconnection of the transmission systems of the islands of Lanai, Molokai and Maui with Oahu. Phase I of this independent review included an initial evaluation of the technical configuration and capital costs of establishing an undersea cable system and examining impacts to the existing electric transmission systems as a result of interconnecting the islands. To move forward from the foundational work of the R.W. Beck report [1] and in support of the Hawaiian Clean Energy Agreement, the Department of Energy through the National Renewable Energy Laboratory contracted Electranix Corporation to study the undersea cable system necessary to transmit 400 MW of wind energy from the islands of Lanai and/or Molokai to Oahu (Stage 1) and the future installation of a 200-MW capacity cable system to interconnect the island of Maui (Stage 2).

The study effort included a technical feasibility assessment and budgetary cost estimate of the undersea transmission interconnect options. Inputs from the suppliers of undersea power cables and direct current (DC) converter station has been provided. Six DC cable options and one AC cable option were selected from 18 alternative configurations derived from a previous study [1]. Only one of the selected options included undersea cable transmission between Lanai and Molokai whereas all the alternatives from this previous study included undersea cable transmission between the two islands. The economic justification for undersea cable transmission between Lanai and Molokai could not easily be established, so the feed to Oahu from these islands was radial only.

The AC option was only considered viable if three core XLPE cable can be applied, but which is limited by the depth to which it can be laid because of its weight. Consequently it is precluded for feeding into Oahu. However, it could be used to interconnect Molokai and Lanai, and which was investigated for one option.

The technology for the six DC options is voltage sourced converters (VSC). VSC converters create a stable AC supply for wind turbine generators to connect into. They also offer a significant buffer to AC system faults at one end adversely impacting the AC system at the other end. The wind turbine generators on Molokai and Lanai will not be affected significantly by severe AC system faults on Oahu.

With a suitable control strategy for the VSC transmission, it will be possible to maintain a steady AC voltage and frequency for the sending end wind farms. This means that a direct and conventional interconnection to the small local load on Molokai or Lanai may be possible. It is only when the DC cable transmission is completely taken out of service that the interconnection to local load would have to be transfer tripped.

The capital costs for the six DC cable transmission options are assembled from the responses of the cable and equipment suppliers. The stated accuracy of these costs is ±20%, and so the estimated values are the lowest provided by the suppliers plus 20%. Case A1-2(a) has a 200-MW DC connection between Lanai and Molokai and Case A1-2(b) has a 200-MW AC connection between Molokai and Lanai, which is slightly lower cost. Analysis (Appendix A) indicates additional justification will be needed to consider a Molokai to Lanai interconnection.

An independent option was proposed by one of the equipment suppliers whose significant benefit is the termination of the Stage 2 transmission from Maui at Lanai or Molokai instead of at Oahu as in the selected options in Table 1. Capital costs are therefore lower because less undersea cable is required, but suffers the disadvantage that power scheduled to Oahu from Maui would only be at the level possible when the wind power being generated on Lanai (and/or Molokai) is below full rating. Power schedules from Oahu to Maui on the other hand would not be restricted below the capacity limits of the converters and undersea cable transmission since any wind power being generated on Lanai and/or Molokai would be displaced accordingly.

Table 1: Budgetary capital costs in 2009 millions of dollars as provided by suppliers of DC cable and DC converter equipment for the DC options.

Option	**C3-2**	**A3-2**	**A1-2**		**B3-2**	**C1-2**	**B1-2**
Description	400 MW Koolau to Molokai	200 MW Molokai to Koolau, 200 MW Molokai to Iwilei	200 MW Molokai to Koolau, 200 MW Lanai to Iwilei, 200MW Lanai to Molokai		400 MW Molokai to Iwilei	200 MW Molokai to Koolau, 200 MW Lanai to Koolau	200 MW Molokai to Iwilei, 200 MW Lanai to Iwilei
			(a)	(b)			
Stations $M	234	288	414	342	234	288	288
Cables $M	154	180	367	424	221	216	245
Total Stage 1 Price $M	388	468	781	766	455	504	533
Stage 2 Maui to Oahu (Approx)							
Converter Stations $M	144	144	117	117	144	144	144
DC Cables $M	420	420	192	192	283	272	272
Total Stage 2 Price $M	564	564	309	309	427	416	416
Total Stages 1 & 2 $M	951	1,032	1,090	1,077	882	920	949

The level of power schedules into or out of the HECO system on Oahu are restrained to the maximum single contingency outage possible, which for this study is 200 MW [2]. Rating the converters and cables above this level requires further investigation.

From a technical perspective, the VSC cable transmission applied to these DC Options is completely viable with little risk of significant problems that would impede its use. The technology is being used to other similar projects of similar rating such as the BorWin Alpha 400-MW offshore wind farm in the North Sea.

Objective of Stage 2

At the Technical Review Committee (TRC) meeting held in Honolulu January 6th and 7th, 2010, the following three scenarios were developed for future Study leading to Stage 2, the connection to Maui.

The objective of the Stage 2 study is to assess the suitability of the three Scenarios developed by the TRC for expanding the Stage 1 development for interconnection to Maui. The TRC agreed that the work should remain focused on 400 MW of wind but emphasized that the study work should articulate that the designs that are modular and have flexibility for expansion.

Description of Stage 2

A significant factor in the Stage 2 development is the application of AC cable between Molokai, Lanai, and Maui, with the undersea cables from Molokai and Lanai to Oahu as HVDC cables with voltage sourced converters (VSC). The three Scenarios developed are presented as follows:

Scenario 1: DC Cable Oahu to Molokai, AC cable Molokai to Lanai

400 MW DC	Oahu to Molokai
230 kV AC	Molokai to Lanai

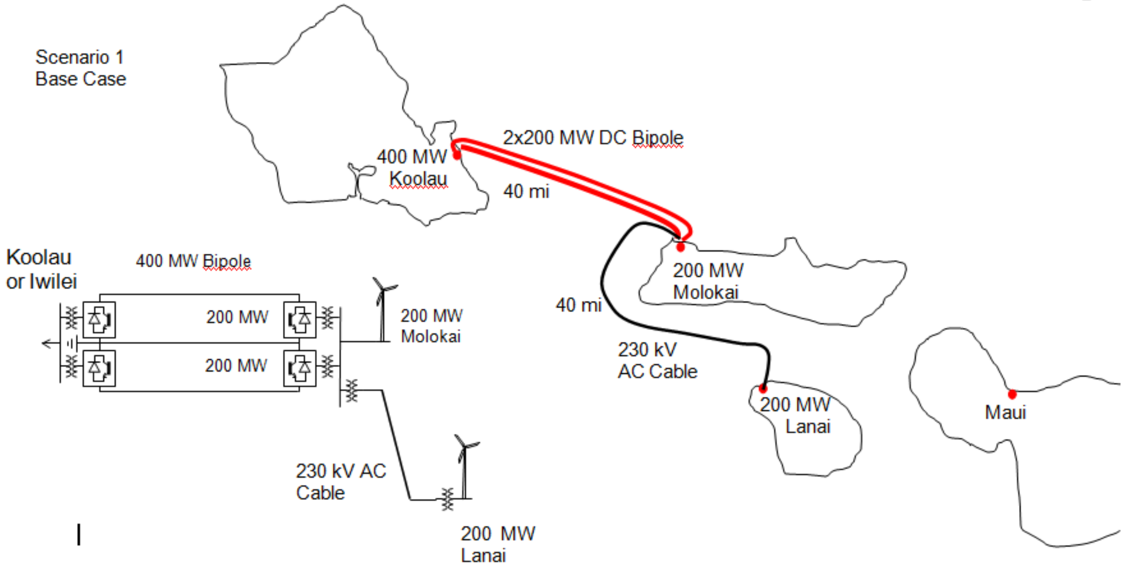


Figure 1: Scenario 1 where the bipole cables can terminate at Koolau or Iwilei on Oahu

Scenario 1 is developed out of the Stage 1 report and does not include any interconnection to Maui. The AC cable between Lanai and Molokai is a three-core, XLPE cable, with a 630 mm^2 copper conductor on each of the three phases as shown in Figure 2. Its weight is 78 kg/m and its diameter is 215 mm (8.5”). This cable has over 200-MW capacity, but it must be 100% compensated with fixed shunt reactors at each end. This is a very heavy cable and as a result can only be laid in relatively shallow water. This precludes its use to Oahu because of the seabed depth is too great for its use. However, it can be applied between Molokai, Lanai and Maui, saving the cost of the VSC converters.

Figure 2: Three-core XLPE undersea cable (courtesy of ABB).

The 100% compensation of the AC cable means that there is minimum reactive power swing since cable charging is fully compensated. It is therefore only the relatively low series impedance of the cable that causes reactive power variations with load. With the AC cable energized only from one end, the 100% compensation also allows for use of pre-insertion resistance using a resistor and two circuit breakers so that the energization is virtually voltage transient free on the interconnection busbar. This alleviates the need for an SVC or STATCOM at this busbar.

Another issue that requires managing is harmonic resonances on the cable. The application of an SVC or STATCOM will not solve these issues and so have little impact on the recommendation to not require them. Further work is needed in this area.

The results for studies with Scenario 1 are summarized in Appendix 2A. With the independent clock synchronizing control on the Molokai converter, there is suitable operational performance so long as the thyristor-controlled resistors are operational to protect the poles from current overload while the nearby wind farm is cut back to the capacity level of the remaining DC transmission if one pole is removed from service. Over-current protection is also available from the VSC controls which act in addition to the thyristor-controlled resistor.

In addition, the overvoltage protection for the dc cable must be protected with a DC chopper at the Oahu (receiving) end of the VSC cable transmission as shown in Figure 3.

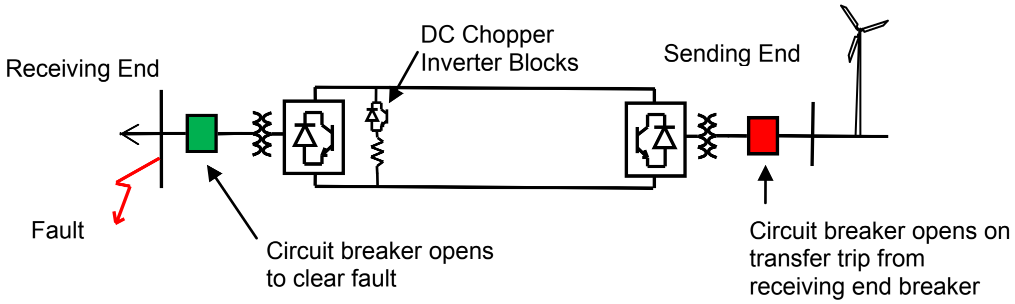


Figure 3: Application of a DC chopper on each pole of the VSC transmission to protect the cable against overvoltage.

Variations in Wind Farm Performance

Generic but detailed Type 3 (DFIG) and Type 4 (Full Converter) wind farm models are represented in the PSCAD models. Each demonstrates different dynamic performance at the low short circuit capacity operating conditions present in these cases.

Scenario 2: A 200-MW Monopole to Iwilei from Molokai and a 200-MW Monopole to Iwilei from Lanai. 69-kV AC Cables Molokai to Lanai, Lanai to Maui and Molokai to Maui

With this scenario the connection is made for the Stage 2 interconnection to Maui as shown in Figure 4.

2 x 200 MW DC	Oahu to Molokai; Oahu to Lanai
3 x 69 kV AC	Molokai to Lanai; Lanai to Maui; Molokai to Maui

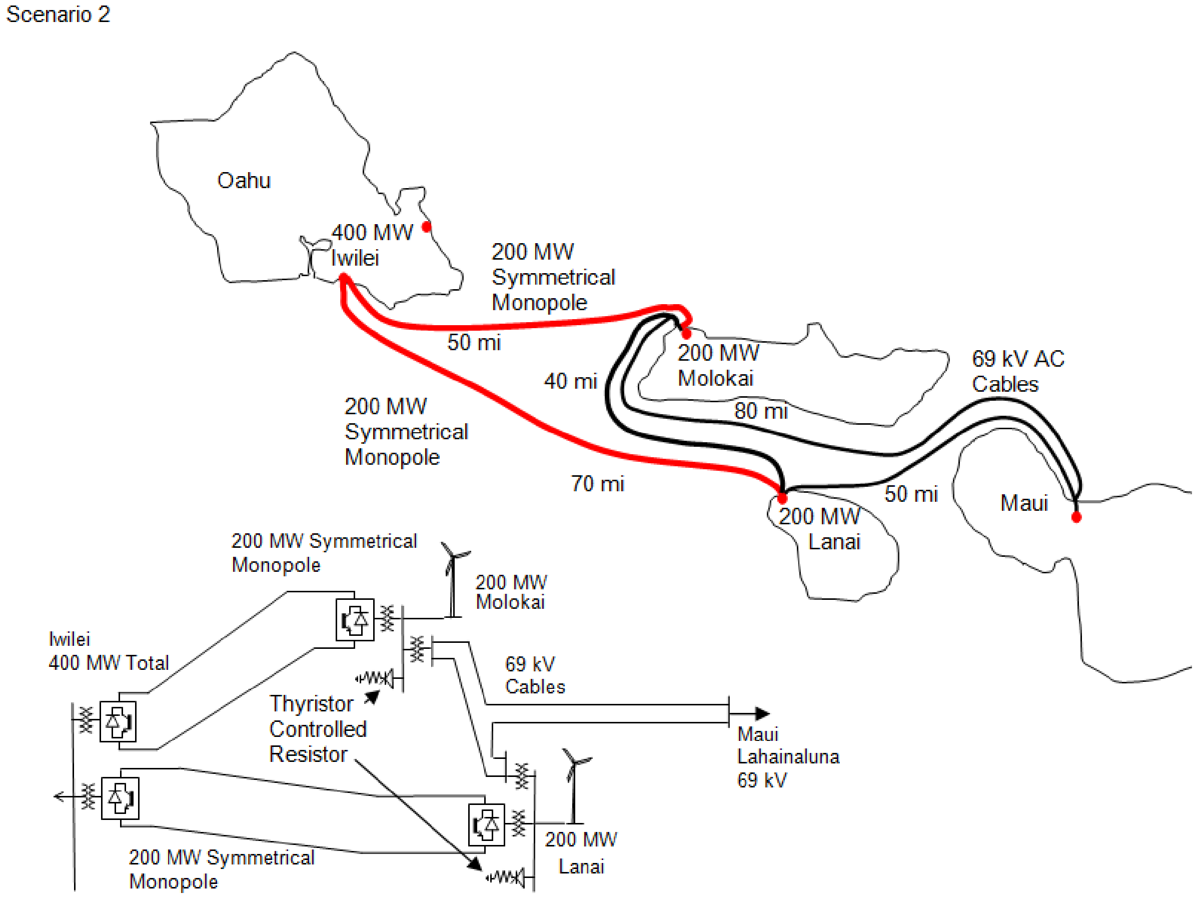


Figure 4: Scenario 2 interconnection of Phase 2 to Maui from Lanai and Molokai

69-kV AC, three-core XLPE cables are applied between the three islands of Lanai, Molokai and Maui as shown in Figure 4. In this instance the longest connection is made to avoid reefs but also to investigate a more severe condition to observe performance. The cables are 100% shunt compensated with fixed shunt reactors at each termination. 1000 mm^2 copper conductors are selected with an 800-A capacity.

The connection to Maui is made to 69-kV Bus 84 Lahainaluna. The Maui power system was translated from PSS/E to PSCAD with all dynamic generators represented.

The detailed simulation studies for the key Scenario cases are in the Appendix.

Operation with Synchronization by independent clock

These studies were originally undertaken with both monopoles at their sending end converters synchronized with an independent clock, connected in phase with each other. Under such controlled conditions, recovery from the faults was effective, the ac frequency on Maui was stable, and all systems stayed synchronized.

Operation with Synchronization by Phase Locked Loop

An attempt was made to synchronize the controls of both VSC monopoles with individual phase locked loops (PLL). This was not possible as the power system on Lanai is not stiff enough to hold the conventional PLLs in steady operation.

In an attempt to ensure the PLL was as robust as possible, two units in series were applied. The resultant synchronizing signal was of good quality, but lacked the phase angle stabilization that is usually provided by inertia to support the Molokai monopole in an acceptable level of performance. This is shown in Figure 5:

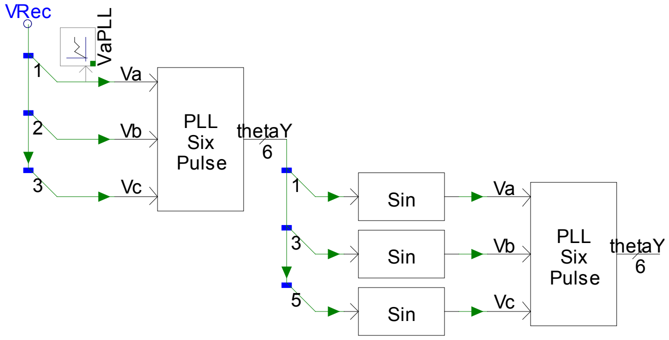


Figure 5: Double PLL for synchronizing the VSC monopole controls

Evidence that the double PLL operated effectively against an extremely poor ac wave-shape is shown in Figure 6. A PLL generates a ramp signal that is synchronized to the 60 Hz wave-shape of the busbar the VSC converter is connected to. This signal ramps from 0 degrees to 360 degrees once per cycle as shown in Figure 6. From this ramp signal, the controls are locked onto to ensure the valves fire in correct sequence to the ac wave-shape. Even though the phase voltage is going through a severe distortion, the two PLLs generate a stable ramp, indicating its robustness.

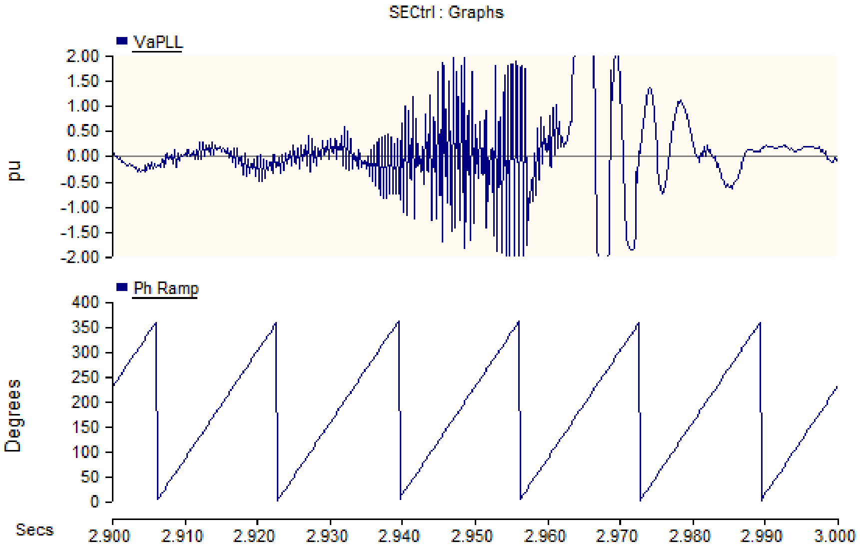


Figure 6: Functional performance of the PLLs on the Molokai monopole where the output of the second stage PLL is plotted as acceptable 60-Hz ramp signals.

Operation with One Monopole on Synchronized with an Independent Clock and the other Monopole with a PLL

Having one monopole synchronized with an independent clock and the other with a PLL is possible although the performance is not as robust as when both monopoles operated from phase synchronized independent clocks. The cases with this hybrid control configuration are tested in the Appendix as Scenarios 2b-1, 2b-2, 2b-3, 2b-4, 2b-5, 2b-6 and 2b-7.

Scenario 3: 400-MW DC Bipole Oahu to Molokai, 138-kV AC 3-Core AC XLPE-Cable Molokai to Lanai, a 3-Core 69-kV AC XLPE Cable each to Lanai to Maui, Molokai to Maui

400 MW DC	Oahu to Molokai
138 kV AC	Molokai to Lanai
2 x 69 kV AC	Lanai to Maui; Molokai to Maui

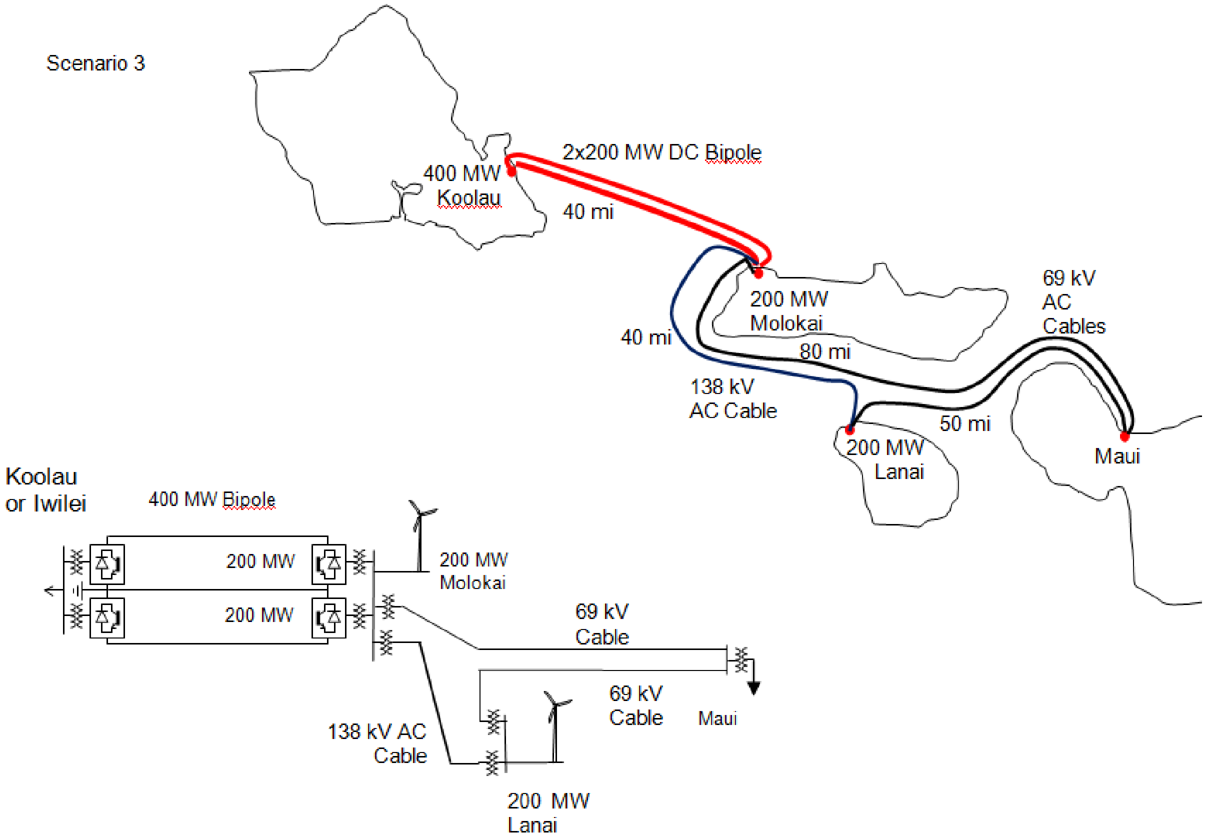


Figure 7: Scenario 3 interconnection of Stage 2 to Maui from Lanai and Molokai

This Scenario 3 operates technically as does Scenario 2 with the same challenges in synchronization. It functions satisfactorily if the VSC converter on Molokai is synchronized with an independent clock that can support the frequency of the islands of Molokai, Lanai and Maui.

Scenario 3 is unable to function with synchronization through a PLL depending on the strength of the Maui system to solidly connect onto.

Control Requirements

A control requirement for both Scenario 2 and Scenario 3 is the synchronization. The method that is proposed is as follows:

1. Of the two VSC cable feeder poles, one pole must be on an independent clock. This provides the frequency control for the interconnected islands of Molokai, Lanai and Maui. This applies if it is configured with symmetrical monopoles as in Scenario 2. If configured as a bipole as in Scenario 3, both poles could be operated as an independent clock providing they are derived from the same clock.

2. The other VSC cable feeder pole is synchronized through a conventional phase locked loop, which it is able to do through the ac voltage at its terminal connecting busbar at its sending end. The frequency is defined by the other VSC cable feeder with the independent clock.

3. The VSC feeder with the PLL control has ability to control power. As such it can be automatically scheduled to transmit power equal to the power on the other VSC feeder with the independent clock. In this way they two VSC feeders will equally control the power to Oahu. Alternatively, the power order to the VSC feeder with the PLL controls can be derived from the power from the wind farms and Maui in such a way that losses are minimized and the VSC feeder with the independent clock does not overload.

4. If the VSC feeder pole with an independent clock is faulted and removed from service, then a control mechanism must be in place to ensure the other pole if operating with a phase locked loop, immediately switches to an independent clock. This is not a trivial control action and must be implemented with care and reliability.

When this control strategy is implemented, the power systems and wind farms on Molokai, Lanai and Maui will be synchronized to each other but not to Oahu. The pole with the independent clock is essentially equivalent to a “swing bus”, which in power system terms is able to absorb and generate the power that the AC system requires to maintain its frequency.

There is a possibility that the frequency that is maintained by the pole with the independent clock can be adjusted as needed to best accommodate the AC power system, either on the islands of Molokai, Lanai, and Maui, or on Oahu. Further work is required to define the frequency control system so that this pertinent information can be included in a technical specification for the Stage 1 feeders. This is to ensure these feeders will be constructed to accommodate the controls needed for the Stage 2 synchronization.

Conclusions

From this study, the following conclusions can be drawn:

1. The application of AC three-core XLPE cables to interconnect the islands of Molokai, Lanai and Maui is a suitable construction method to apply. However, some more engineering is required on the impact of AC harmonic impedances.

2. With VSC converters at Molokai and Lanai at around 200 MW, they can connect to the three islands including Maui with synchronization achieved with independent clocks. These independent clocks must be phased with respect to each other in order to achieve acceptable power exchanges on the AC cables between Molokai, Lanai and Maui.

3. The more conventional method of synchronizing the converter stations using phase locked loops will not work with the wind farms and the small (200 MW) power system of Maui. However, if one pole or monopole at Lanai or Molokai is synchronized with an independent clock, and the other pole or monopole is synchronized with the more conventional phase locked loop technology, then the Stage 2 system can be made to operate satisfactorily.

4. Further study will result in a compromised and acceptable means of synchronizing the voltage sourced converters at Molokai and/or Lanai to ensure best operational performance of the wind farms on Molokai and Lanai, and with the Maui system. In particular additional work is required to ensure the synchronization and frequency control strategy is clearly defined for a technical specification for the Stage 1 VSC feeders to Oahu.

References

1. R.W. Beck, "Hawaii Inter-Island Cable Study", Draft report to the Department of Energy, May 15, 2009.
2. NREL Report: "Oahu Wind Integration and Transmission Study (OWITS) Hawaiian Islands Transmission Interconnection Project", NREL Subcontract No. LAM-9-99436-01, by Dennis Woodford, Electranix Corporation, May 8, 2010.

APPENDIX

Simulation Studies for Scenarios 1, 2 and 3 Inter-Island DC Cable Options

Introduction

The detailed PSCAD model of the inter-island DC cable options was developed for testing the technical performance of the options proposed for incorporating the future connection to Maui. At the Technical Review Committee (TRC) meeting held in Honolulu January 6th and 7th, 2010, the following three scenarios were developed:

Additional cases will be run (each with 200 MW of wind on Molokai and 200 MW of wind on Lanai) which include an AC loop (69 kV or 138 kV) connecting Maui to Molokai and Lanai:

1.	400 MW DC	Oahu to Molokai
	230 kV AC	Molokai to Lanai
2.	2 x 200 MW DC	Oahu to Molokai; Oahu to Lanai
	3 x 69 kV AC	Molokai to Lanai; Lanai to Maui; Molokai to Maui
3.	400 MW DC	Oahu to Molokai
	138 kV AC	Molokai to Lanai
	2 x 69 kV AC	Lanai to Maui; Molokai to Maui

The TRC supported the evaluation of these three cases as the next steps for the HVDC study work. The TRC agreed that the work should remain focused on 400 MW of wind but emphasized that the study work should articulate that the designs that are modular and have flexibility for expansion.

The TRC requested that the various studies be integrated into a single life cycle cost benefit analysis for the cable project.

Scenario 1 – Base Case

The requirement for 400-MW HVDC undersea cable transmission from Molokai to Oahu was achieved with a bipole configuration into Koolau as shown in Figure A-1.

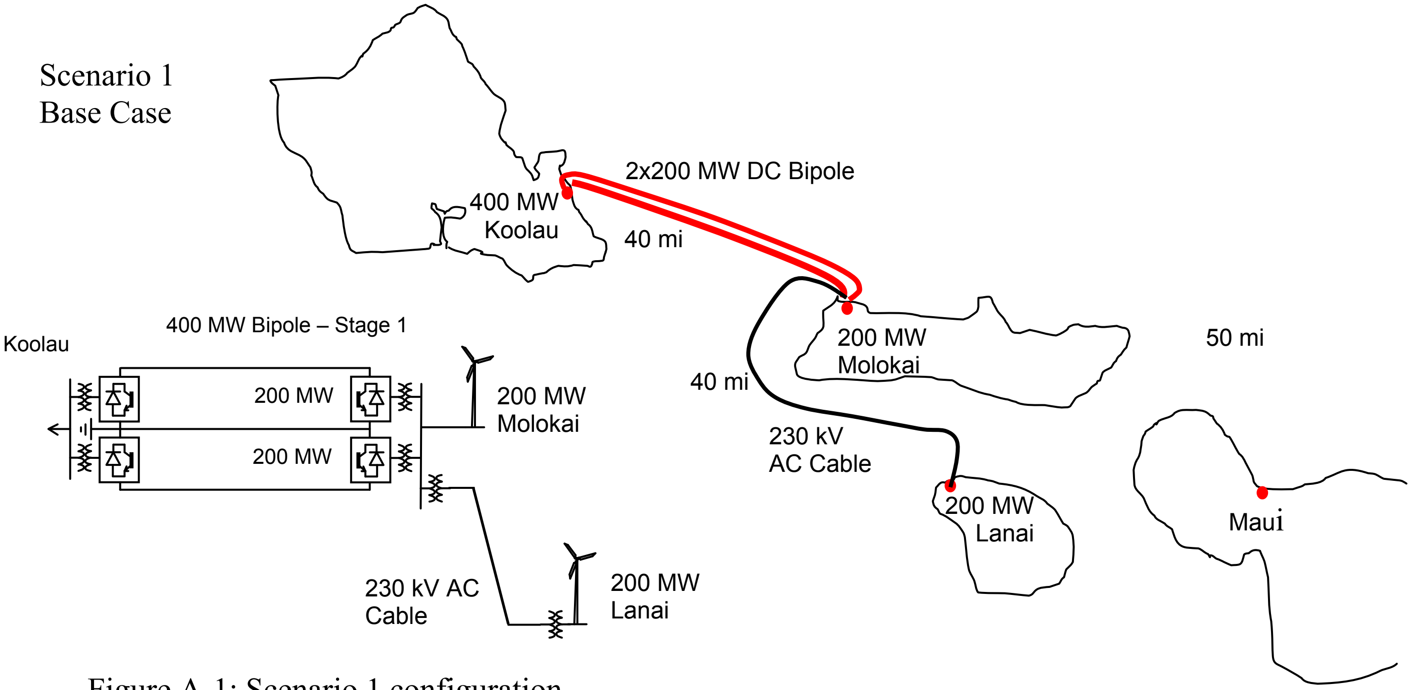


Figure A-1: Scenario 1 configuration

The controls of the HVDC converter at Oahu end include a DC crowbar chopper to protect the DC cable from overvoltage.

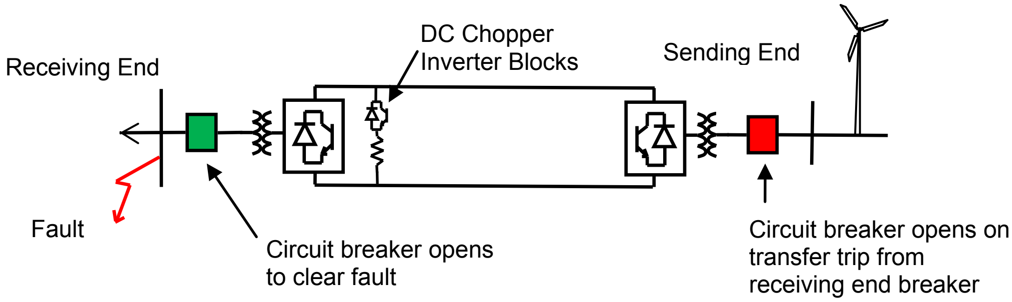


Figure A-2: DC crowbar chopper for DC cable overvoltage protection

List of Scenario 1 Cases:

1: 3 phase fault, 200 msec at Iwilei on Oahu. Both symmetrical monopoles remain in service.

2: 3 phase fault, 200 msec at Iwilei on Oahu. Lanai to Oahu symmetrical monopole removed from service.

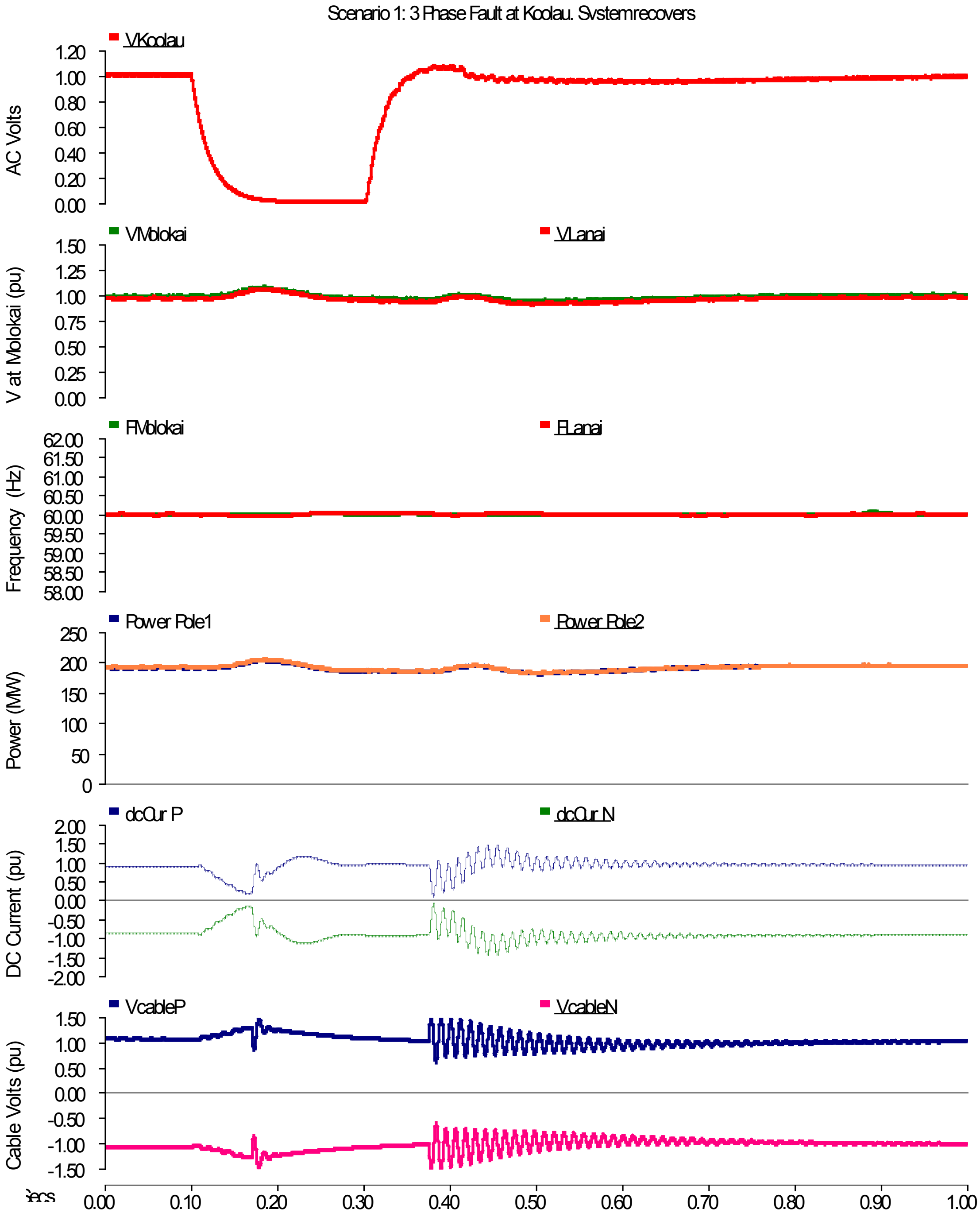
3: 3 phase fault, 200 msec at Iwilei on Oahu. Molokai to Oahu symmetrical monopole removed from service.

4: 3 phase fault at Molokai for 200 msec. The Lanai to Molokai 69-kV cable removed from service.

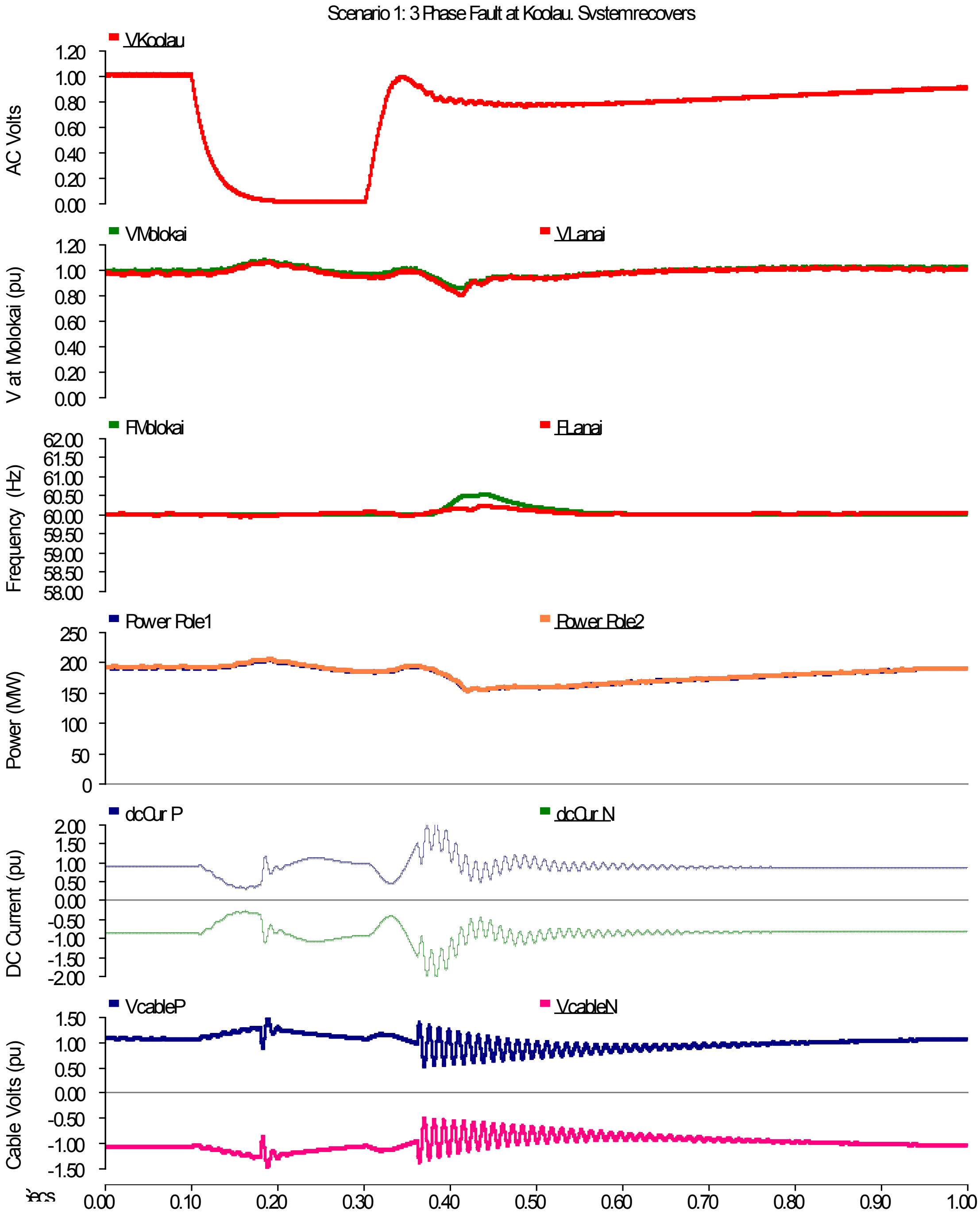
5: 3 phase fault at Lanai on the 69-kV AC cable between Lanai and Maui, which is cleared and removed from service.

6: 3 phase fault at Molokai on the 69-kV AC cable between Molokai and Maui, which is cleared and removed from service.

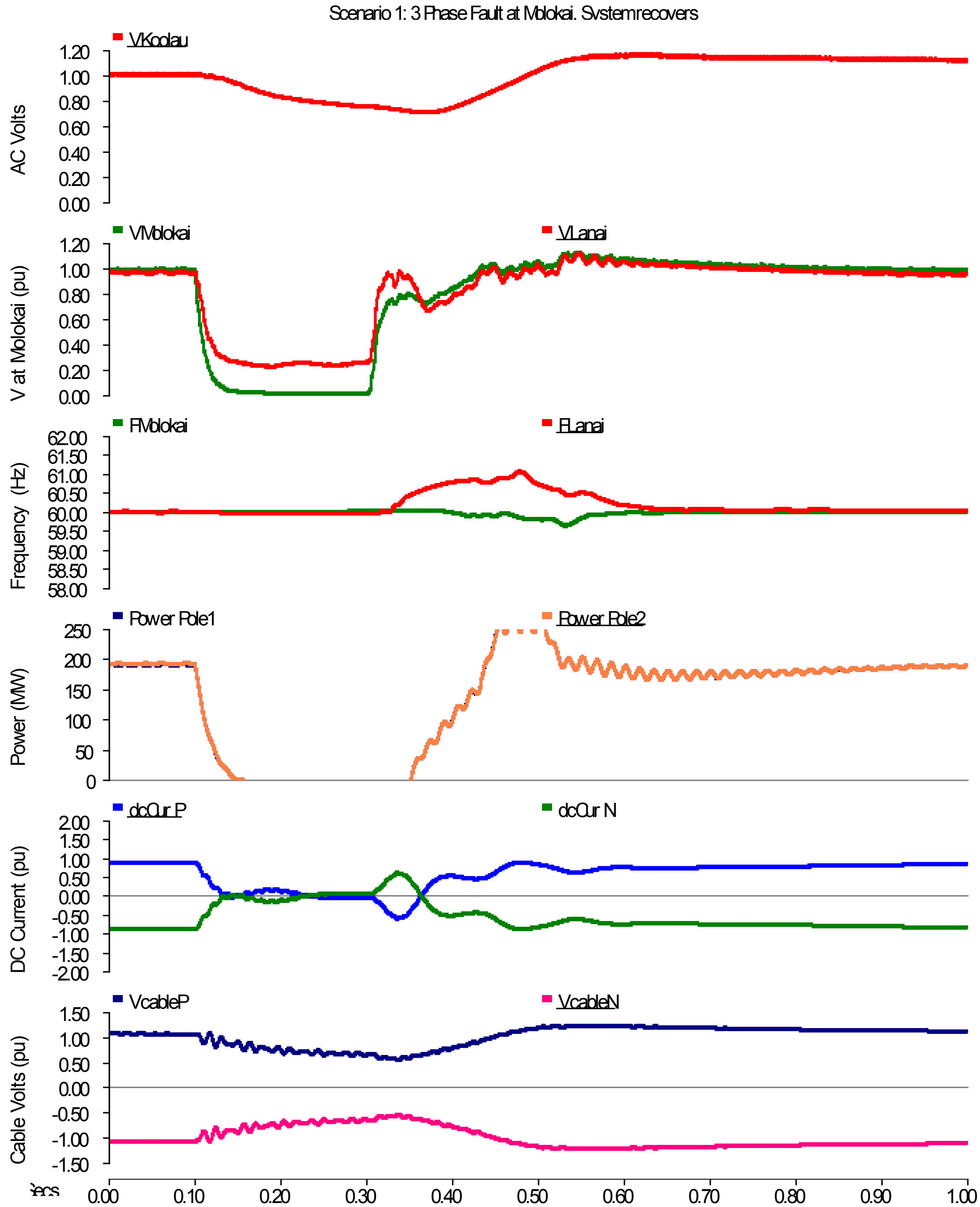
7: 3 phase fault at Bus 971 in the 33-kV AC system on Maui with the 300-MW KPWI generator cleared.



In this case, the inverter is blocked when the crowbars at the Oahu end of the DC cables are operating. This is because the sending end dc current includes the crowbar current plus the inverter current. By blocking the inverter when the crowbar is operating, the sending end current does not exceed its rated value.



When the inverter remains operational during the period of time the crowbar is blocked, the DC current at the rectifier is overloading as shown in this case. In order for the sending end (wind farm) ac voltage from becoming too excessive, the sending end converters must not block. Then the sending end ac voltage can be controlled.



With a severe AC system fault at the wind farms at the sending end, the system recovers without any dc current overload.

The most severe overload condition comes when one DC pole blocks, such as might occur with a control or protection fault. There is not enough time to transfer trip a wind farm. The options are:

1. The wind turbine generators would be equipped with a fast power reduction feature that will reduce power to 50% of full-load power within a cycle. This can be accomplished with full converter wind turbine generators and also DFIGs to perhaps a lesser extent. They would have to respond to a signal received from the HVDC pole that suffers the inadvertent block. The back-up operation would be the shut-down of the remaining HVDC operating pole, resulting in a 400 MW total outage.
2. Provide an AC thyristor-controlled resistor as an extra facility on the sending end ac system. When the pole is blocked, it kicks in for a period of time until a suitable number of wind turbine generators can be taken off-line by transfer tripping or other means.

The thyristor-controlled resistor could be directly connected to the 33-kV busbar of the wind farm at its main substation. It could be sized in 100-MW blocks. No cooling, filters, or special controls are required. An air cored reactor might be applied as a commutating reactor.

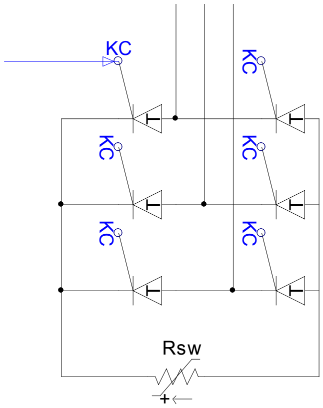
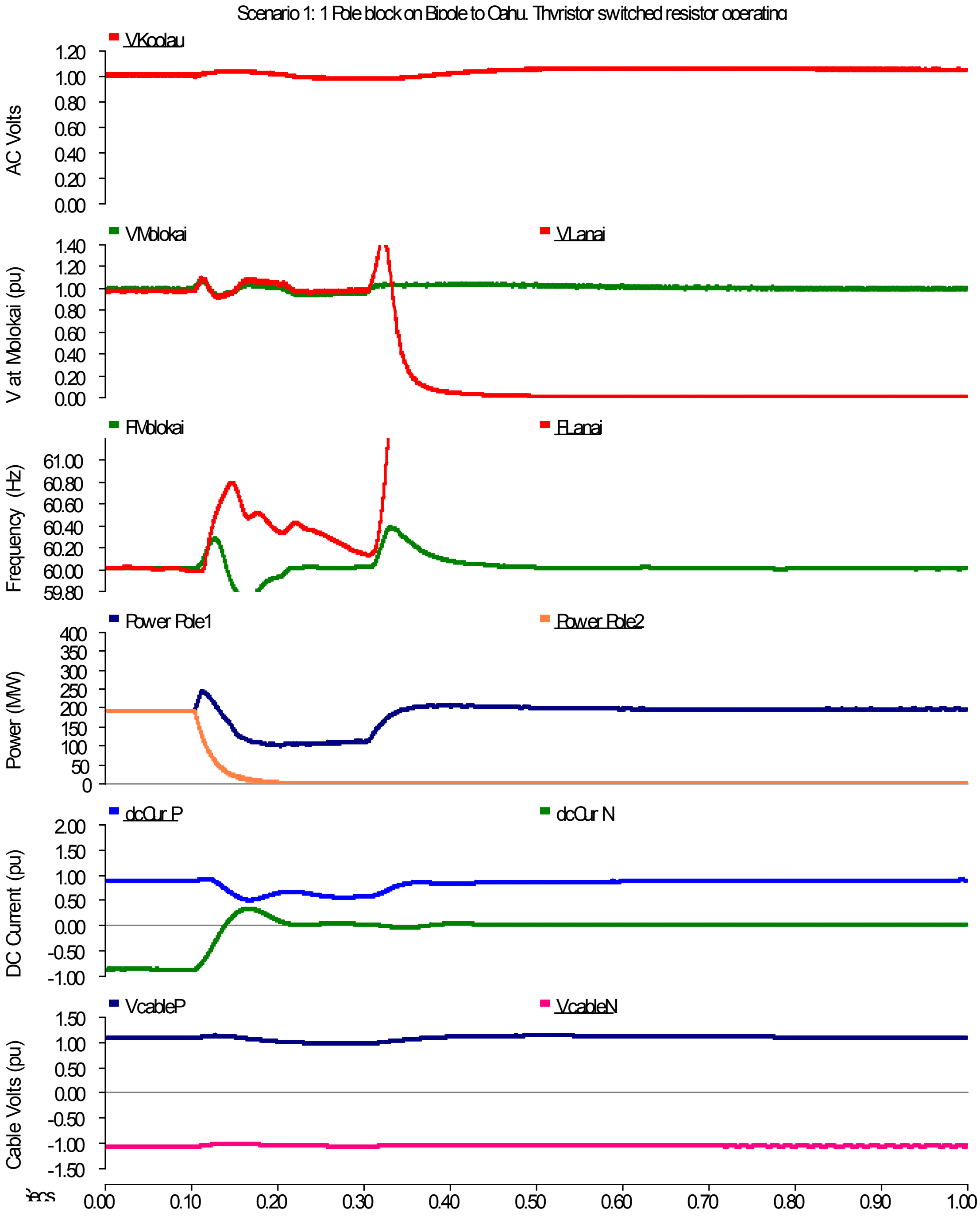


Figure A-3: Simplified thyristor switched resistor configuration



The thyristor-controlled resistor rated at 200 MW kicks in when the one pole inadvertently blocks. It stays in until all the excess wind turbine generators can be switched out.

Simulation Studies for Scenario 2 Inter-Island DC Cable Options with Maui Connection

Introduction

The detailed PSCAD model of the inter-island DC cable options was developed for testing the technical performance of the three scenarios proposed for incorporating the future connection to Maui. At the Technical Review Committee (TRC) meeting held in Honolulu January 6th and 7th, 2010, Scenario 2 was developed.

Scenario 2.

200 MW DC ±150 kV	Oahu to Molokai
200 MW DC ±150 kV	Oahu to Lanai
69 kV, 3 Phase AC	Molokai to Lanai; Lanai to Maui; Molokai to Maui

Scenario 2 – Base Case

The requirement for the two 200-MW HVDC undersea cable transmission from Oahu to Molokai and from Oahu to Lanai was achieved with a symmetrical monopole configuration from Iwilei as shown in Figure A-4.

Also shown in Figure A-4 is a thyristor-controlled resistor at both the Molokai and Lanai wind farms. Whenever one of the DC cables or converters fail, it is required that the wind farm feeding that failed DC cable of converter be taken out of service so that its power generated does not pass through the remaining DC cable and converter left in service causing it to overload. In order to provide time to trip out the wind farm, allowing for back up protection to operate, the thyristor-controlled resistors temporarily switch into service preventing main VSC converter overloads and allowing time for the wind farm to be transfer tripped off line.

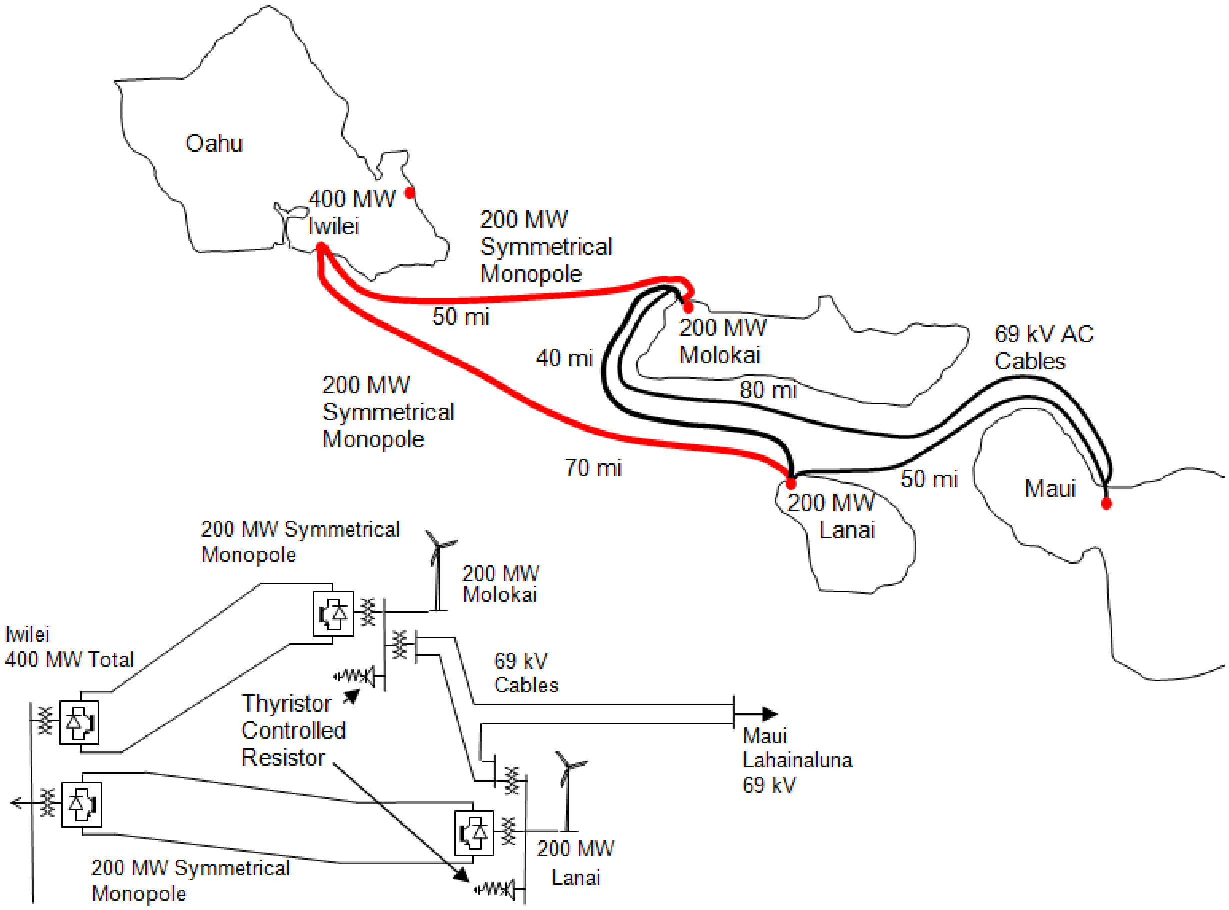
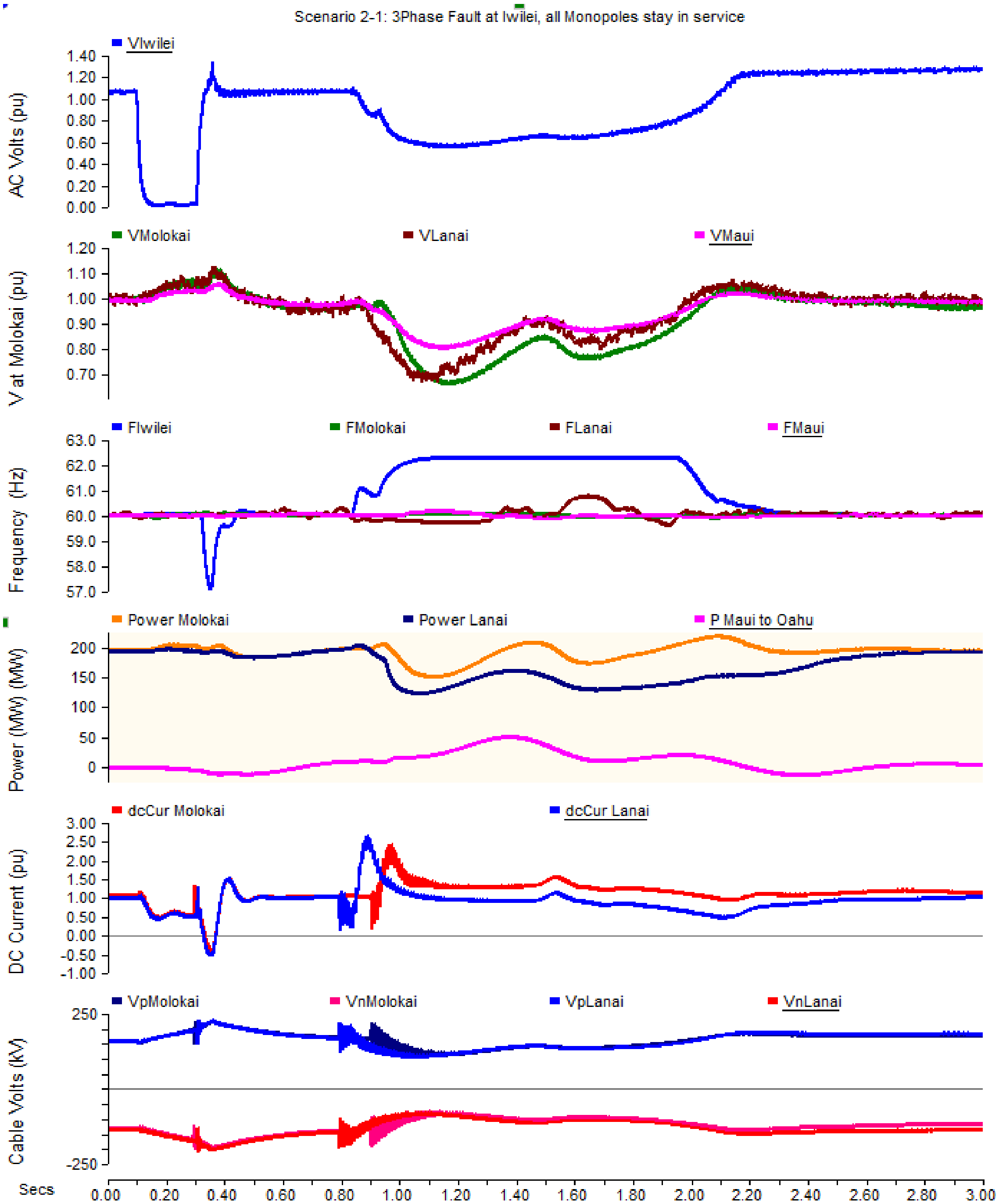


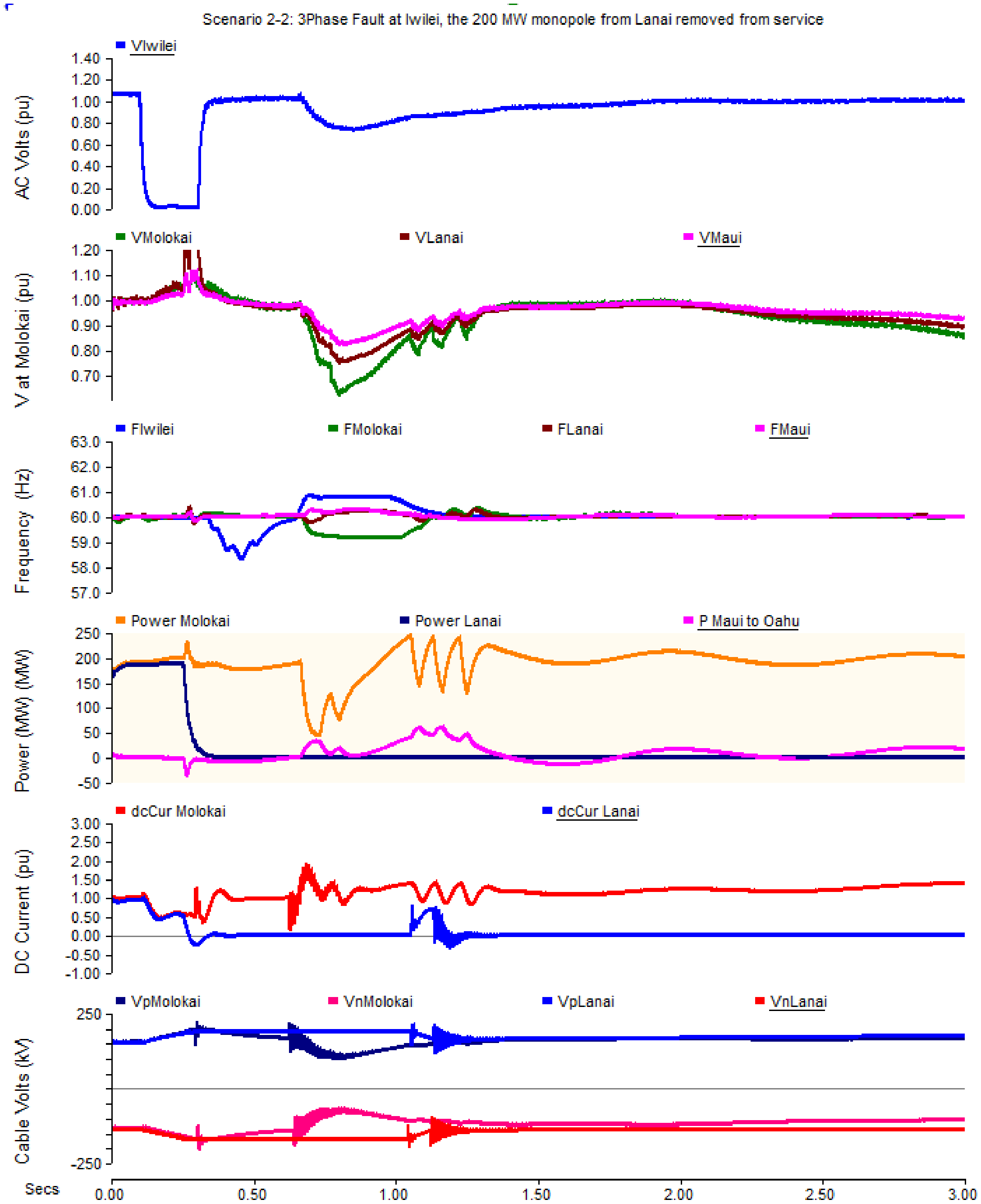
Figure A-4: Scenario 2 cables for interconnecting to Maui in Phase 2.

This first disturbance to Scenario 2 is with all cables and converters in place, with full wind on both Molokai and Lanai. There is no scheduled power interchange with Maui. The disturbance is a 3-phase-to-ground fault at Iwilei, from which all converters and cables recover. The shake-up is most severe to HECO's system on Oahu, but it is also felt right through to Maui. AC frequency is controlled by independent clocks on the Molokai and Lanai 200-MW VSC converters. The ac system on Maui is a heavy load condition so that the VSC converters on Lanai and Molokai are the reference synchronizing frequency source.

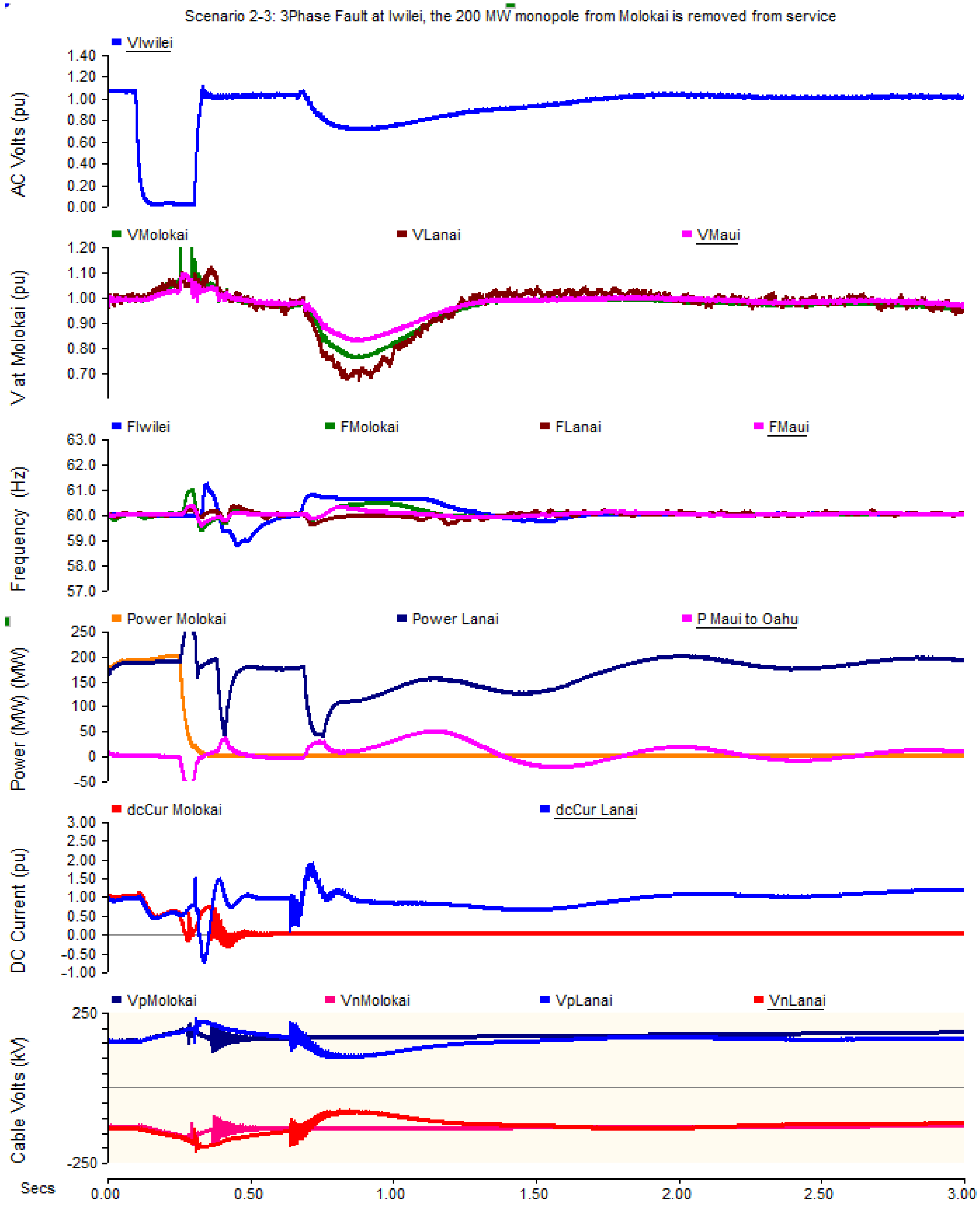
The reference frequency source of the VSC converters on both Molokai and Lanai are strong enough to hold the Maui system in synchronism. The wind turbine generators on Molokai are modeled as generic Type 3 (DFIG) and on Lanai as generic Type 4 (Full Converter). They exhibit different responses as a consequence.



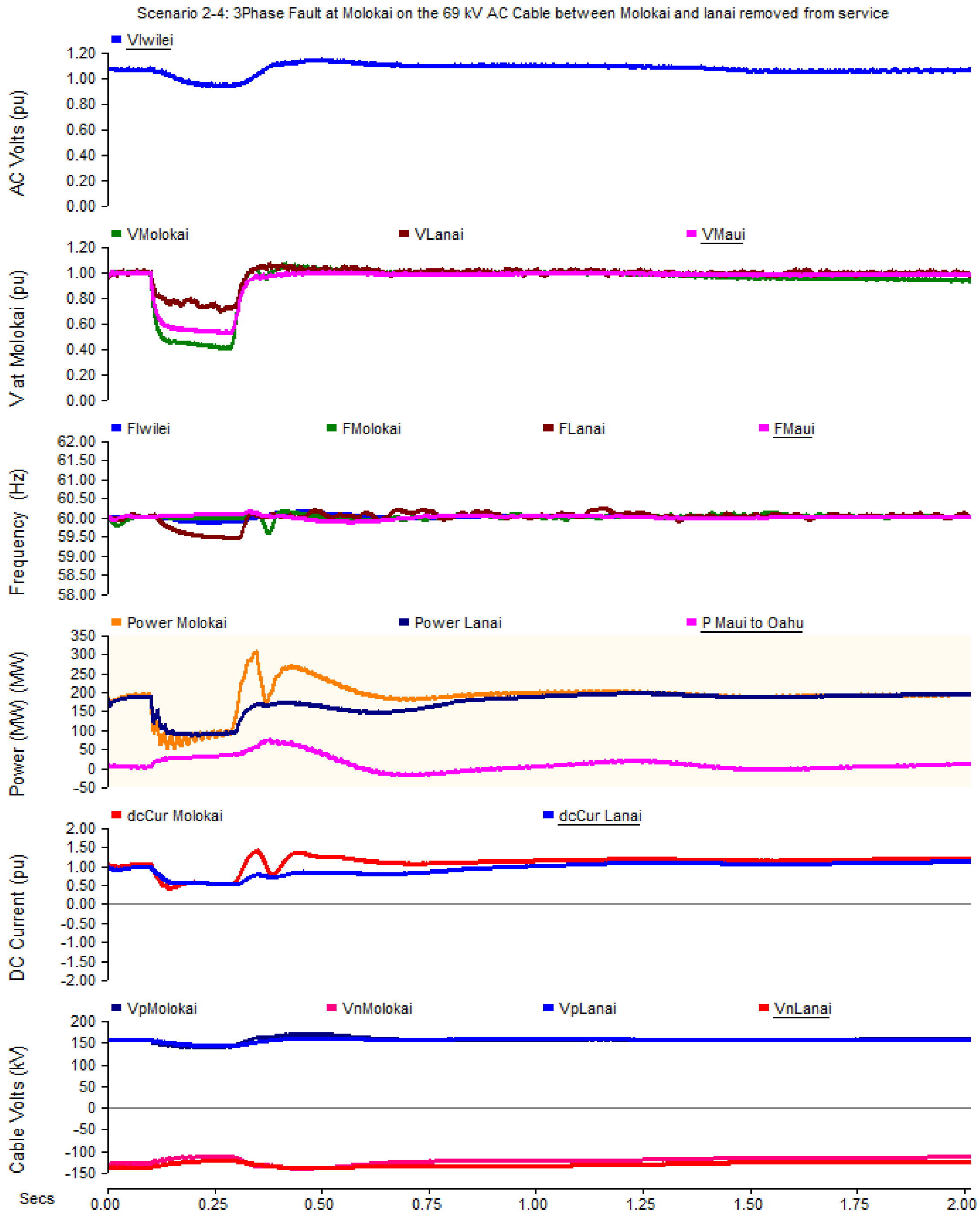
In this case, the inverter is blocked when the crowbars at the Oahu end of the DC cables are operating. This is because the sending end DC current includes the crowbar current plus the inverter current. By blocking the inverter when the crowbar is operating, the sending end current does not exceed its rated value. However, when the crowbar is relieved and the VSC inverters resume their operation, a DC current surge at near 1.0 second is observed.



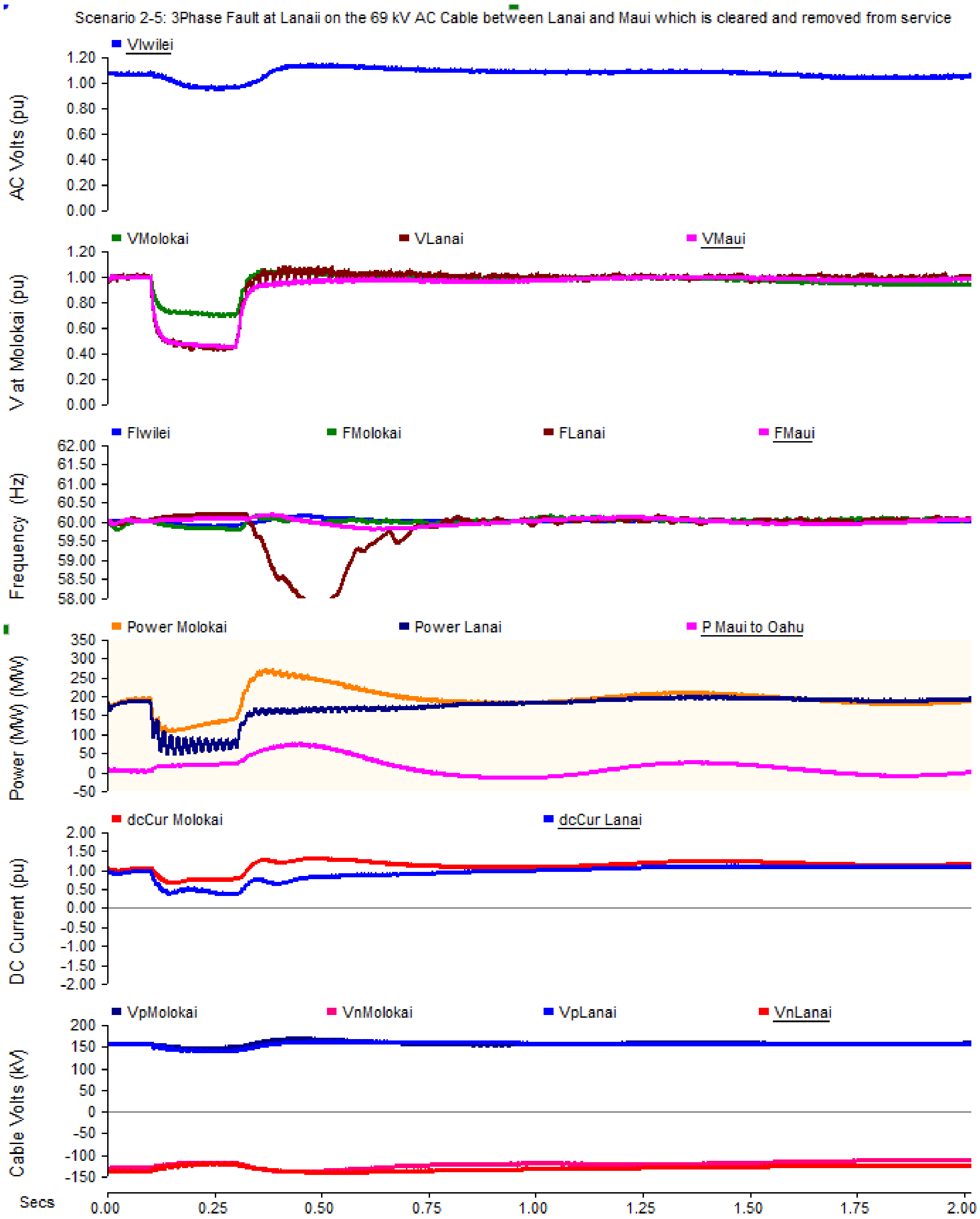
In this case, the severe three-phase-to-ground fault at Iwilei causes the Lanai to Iwilei VSC 200-MW monopole to trip out of service. The 200-MW Lanai wind farm is transfer tripped to ensure that the remaining HVDC cable transmission from Molokai is able to accommodate the remaining power of its wind farm and power swings from the Maui system. At 1.0 seconds, the thyristor-controlled resistor operates for several hundred milliseconds at the same time that there is a power swing from Maui but it stays synchronized to Molokai.



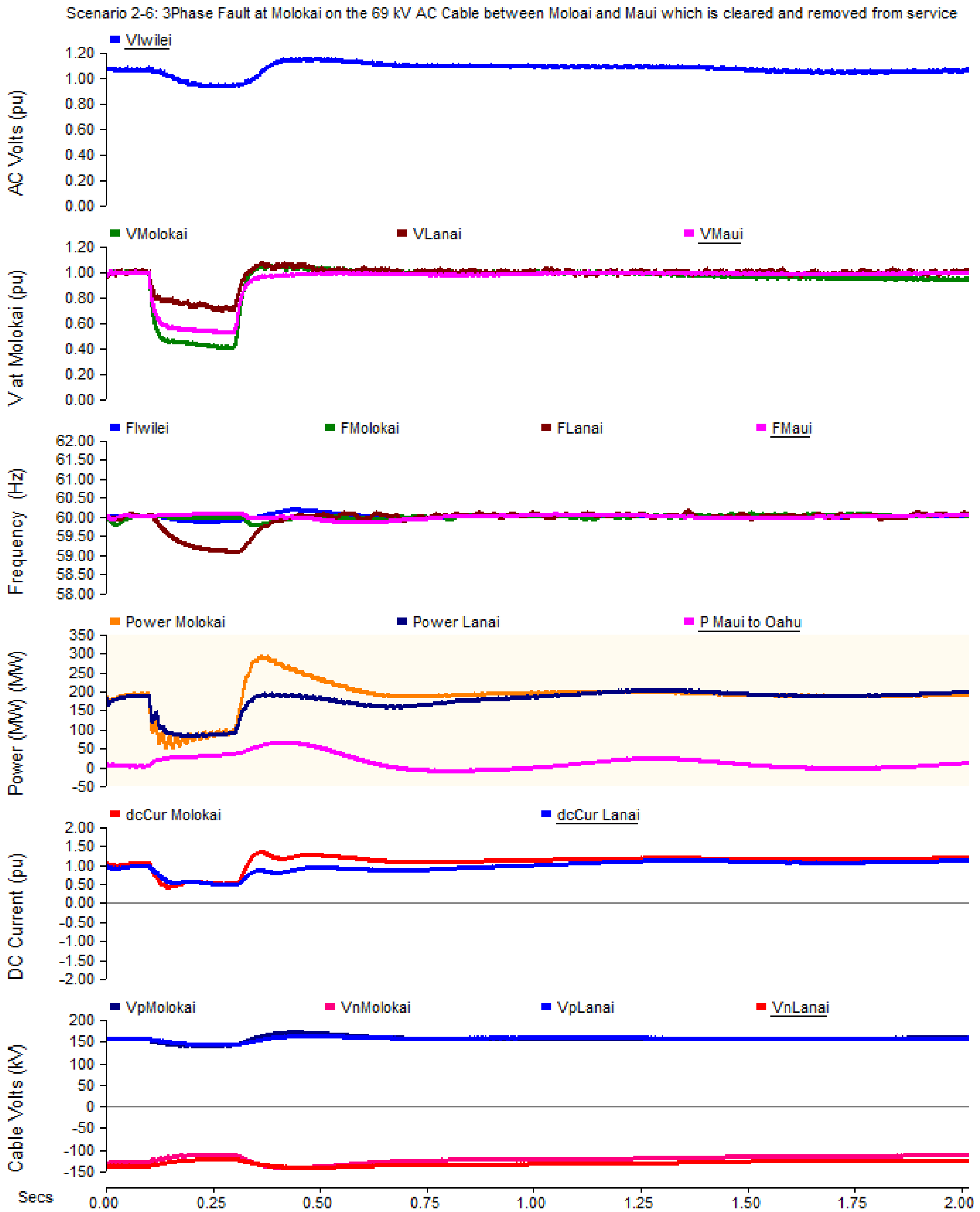
This is the same fault as Scenario 2-2, where there is a severe three phase to ground fault at Iwilei, except this time it is the Molokai 200-MW monopole that comes down. Consequently the Molokai 200-MW wind farm is transfer tripped so the operating 200-MW monopole from Lanai Iwilei is not overloaded. Maui stays synchronized to Lanai.



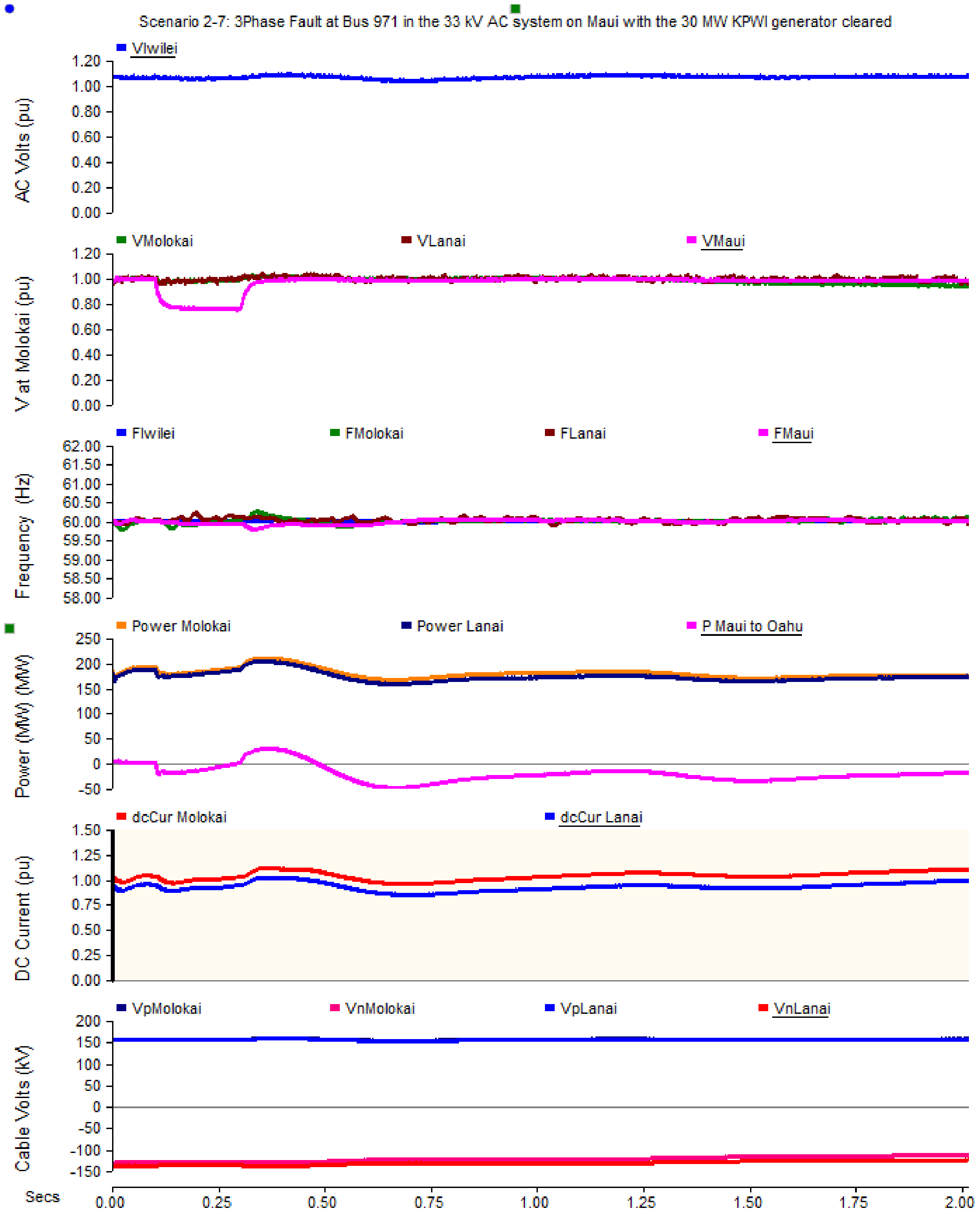
For this AC cable fault there are no real control issues. The two VSC cable transmission systems recover although the thyristor-controlled resistor at Molokai switches on once when the fault is cleared.



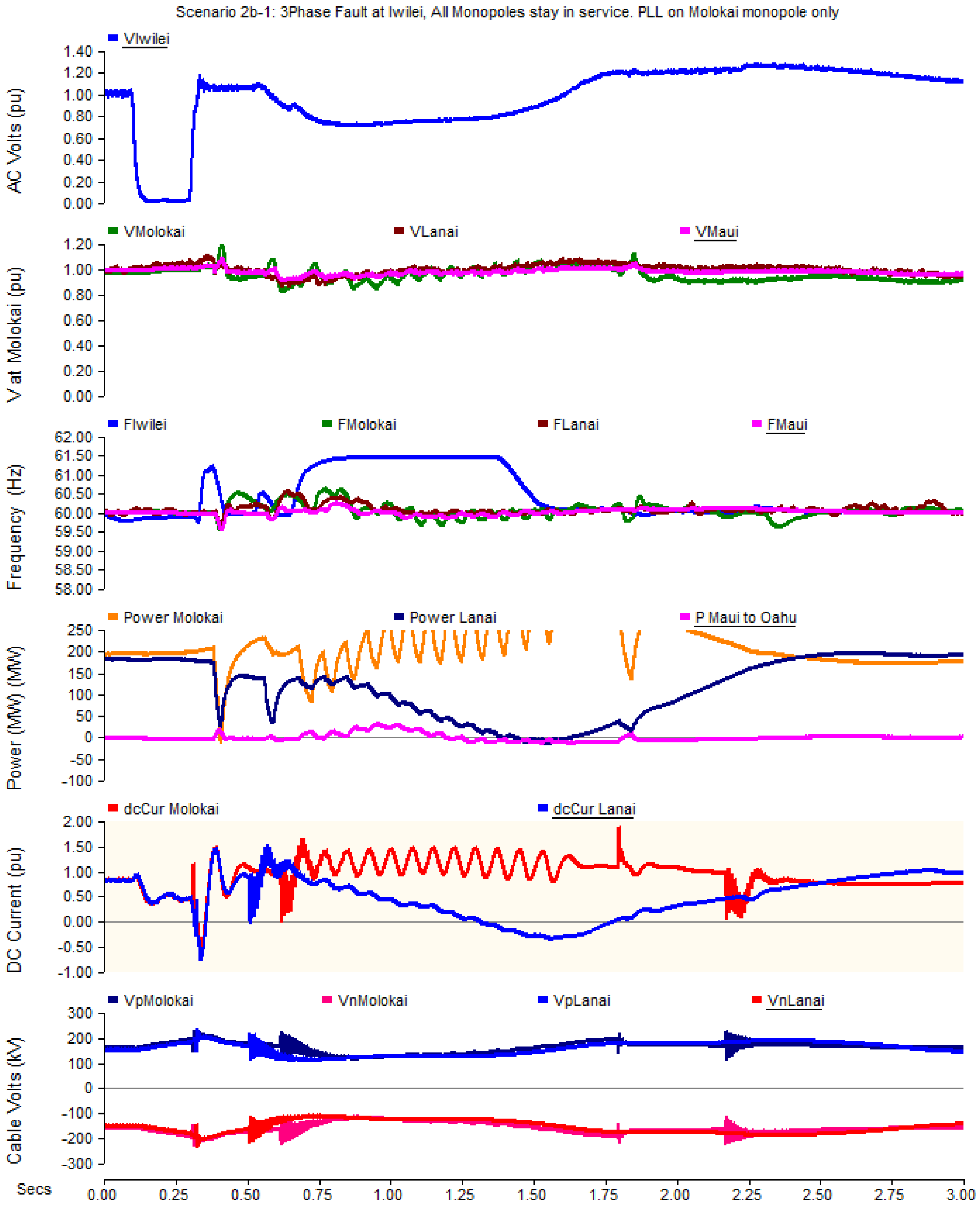
There are no real issues with this AC cable fault. The DC cables and monopoles that remain in service recover nicely and resume operation. The Maui system stays synchronized with the VSC converters at Molokai and Lanai.



There are no real issues with this AC cable fault. The DC cables and monopoles that remain in service recover nicely and resume operation. The Maui system stays synchronized with the VSC converters at Molokai and Lanai.



The loss of 30 MW of generation on Maui, amounting to one of the largest units on line resulted in little impact. Power was automatically supplied from Oahu where wind generation from Lanai and Molokai and frequency generated by the independent clocks on the VSC converters kept the Maui system quite solid.



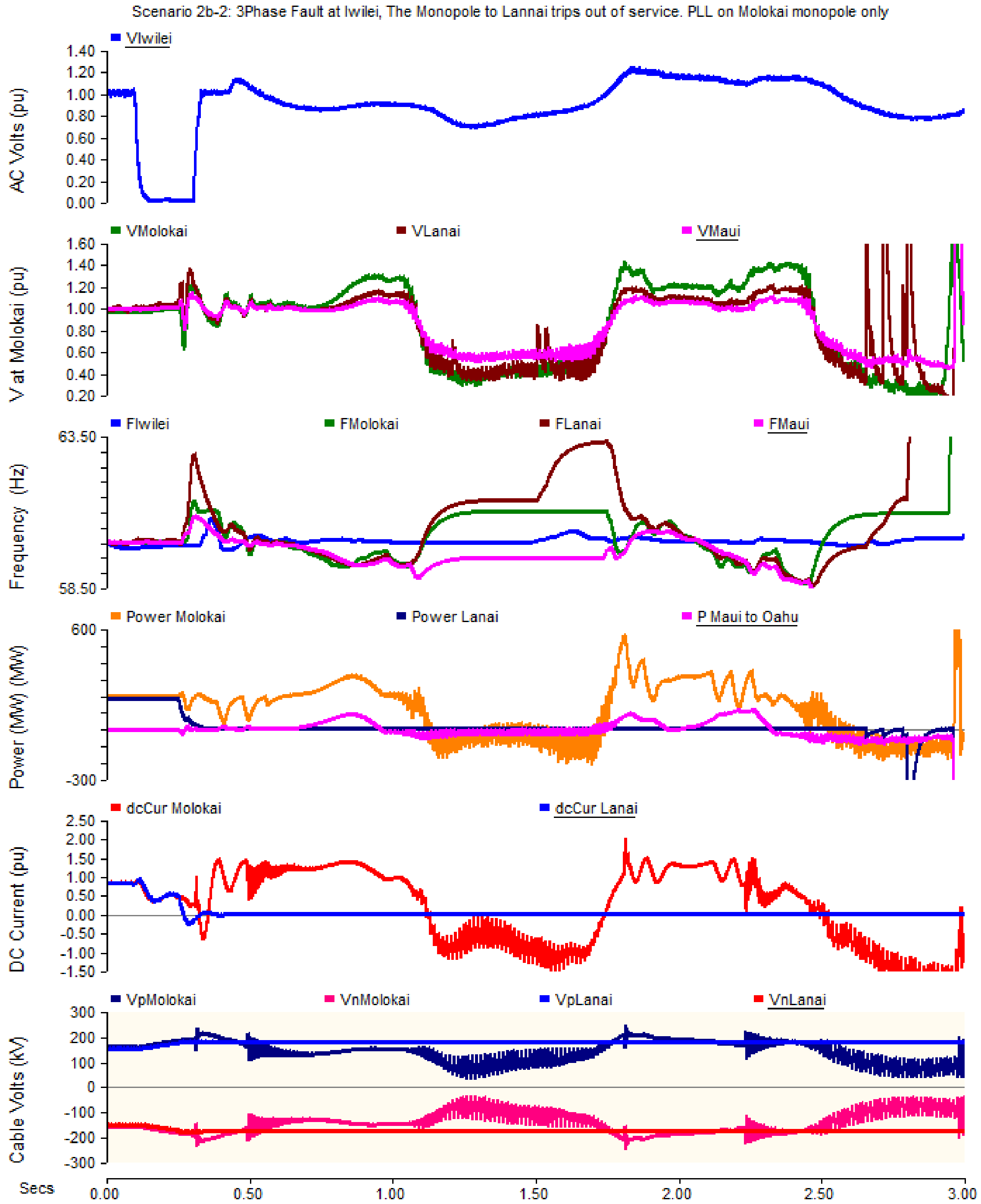
The recovery is not as clean as when both monopoles are operating with independent clocks as in Scenario 2-1. The thyristor-controlled resistor is operational between 0.7 seconds to 1.7 seconds. The dc overvoltage protection for the cables is operational at approximately 0.3 seconds and 1.8 seconds.

Synchronizing the Operation of the Molokai and Lanai Monopoles

A critical control factor for the operation of the two monopole converters is the means of synchronizing their operation with the wind farms on Molokai and Lanai and with the established power system on Maui. Each monopole at 200-MW capacity can operate with the wind farms on Molokai and Lanai and the 200-MW power system on Maui if they apply an independent clock. The disadvantage is there is less over-current control on each monopole, requiring the thyristor-controlled resistor to switch on if the monopoles approach their over-current limit. In addition, the phasing of the independent clocks on each monopole must be synchronized through a high speed fiber telecommunication link.

Tests show that if a phase locked loop (PLL) is applied at each monopole based on the ac voltage at their Molokai and Lanai terminals, their combined strength together with the strength of the Maui system is inadequate to hold their controls of the two 200-MW monopoles in synchronism by normal means. An intermediate step was applied where the Molokai monopole was synchronized through a PLL to its local AC voltage while the Lanai monopole retained its independent clock, phased to the Maui power system. A control was applied to the Molokai PLL controls to measure and maintain the power into and out of Maui to an operator controlled level. The result of this control was that the variability of the wind power on Molokai and Lanai was buffered from impacting Maui and all variability was transferred to Oahu through the Molokai monopole.

The application of the independent clock on the Lanai monopole provided stabilization to the PLL controls on the Molokai monopole. When the disturbance from a three phase fault at Iwilei on Oahu precipitated a failure in the Lanai monopole so that it tripped out of service, the remaining monopole with its PLL synchronized to the ac system bus was unable to maintain suitable synchronism. This disturbance is shown as Scenario 2b-2: 3 phase fault at Iwilei. The monopole to Lanai trips out of service. PLL on Molokai monopole only. When results of this case are reviewed and compared to Scenario 2-2 where the Molokai monopole has an independent clock, then the performance is clearly unacceptable. The wind farm on Lanai is transfer tripped when the Lanai monopole is blocked and shut down. The power from the Molokai wind farm should be able to be transferred on the Molokai monopole to Oahu.


Scenario 2b-2: 3Phase Fault at Iwilei, The Monopole to Lannai trips out of service. PLL on Molokai monopole only

The single Molokai monopole with its PLL synchronization demonstrates unacceptable performance when the Lanai monopole with its independent clock is taken out of service. Compare with Scenario 2-2.

In an attempt to ensure the PLL was as robust as possible, two units in series were applied. The resultant synchronizing signal was of good quality, but lacked the phase angle stabilization that is usually provided by inertia to support the Mololai monopole in an acceptable level of performance. This is shown in Figure A-5:

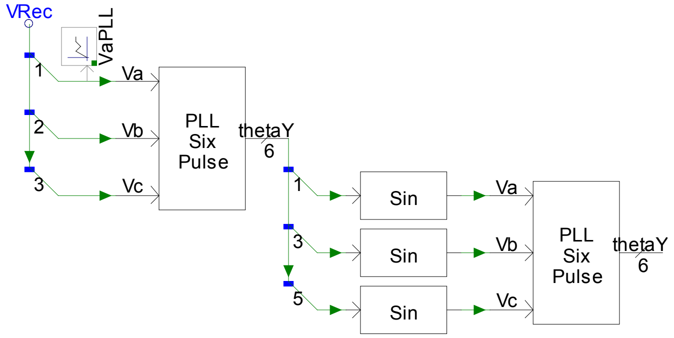


Figure A-5: Double PLL for synchronizing the VSC monopole controls

Evidence that the double PLL operated effectively against an extremely poor AC waveshape is shown in Figure A-6. A PLL generates a ramp signal that is synchronized to the 60-Hz waveshape of the busbar the VSC converter is connected to. This signal ramps from 0 degrees to 360 degrees once per cycle as shown in Figure A-6. From this ramp signal, the controls are locked onto to ensure the valves fire in correct sequence to the AC waveshape. Even though the phase voltage is going through a severe distortion, the two PLLs generate a stable ramp, indicating its robustness.

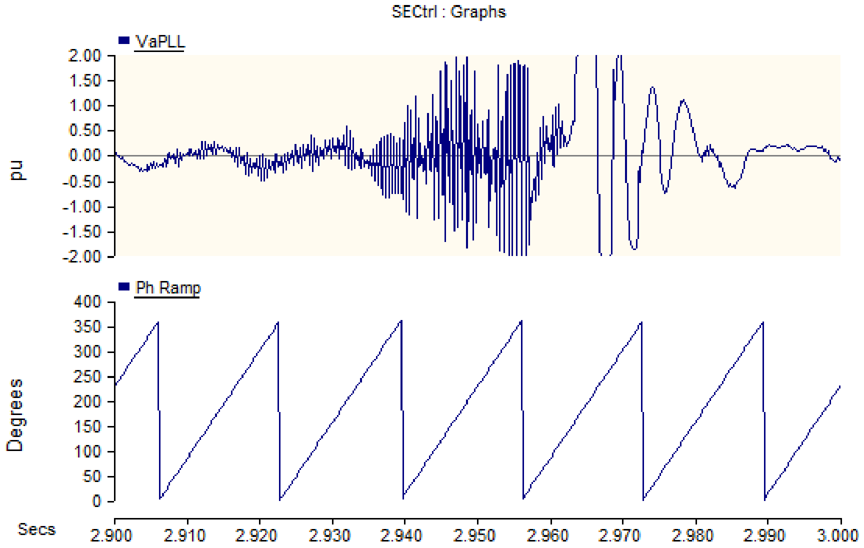


Figure A-6: Functional performance of the PLLs on the Molokai monopole where the output of the second stage PLL is plotted as acceptable 60-Hz ramp signals.

Other factors impact the stability of the ac waveshape including the apparent short circuit capacity that the wind farm is exposed to when still operational on Malokai, as well as harmonic impedance resonant frequencies on the ac cables to Maui. Another factor that reduces the stability of the VSC converter controls with a PLL is the application of the conventional vector control method. This has the advantage of controlling dc current but requires reasonably good ac waveshape stability to be effective. Consequently, significant design will be required to ensure the VSC converters will operate acceptably with the wind farms and the ac system at Maui. The cases run as Scenarios 2-1 to 2-7 in this Appendix indicate that if the VSC converters are synchronized through independent clocks, then satisfactory performance is obtained.

It is possible that a hybrid synchronization control could be applied to the VSC converters on Molokai and Lanai. If stable vector control is not possible with the PLL, then it could be replaced with a more stable control but rely on the thyristor-controlled resistors and DC overvoltage crowbars and transfer tripping to ensure protection from over-currents and over-voltages on the VSC converters.

So long as one of the 200-MW VSC poles is operating off an independent clock, then performance of the VSC transmission to Oahu, the wind farms and synchronization to the Maui system is acceptable.

Simulation Studies for Scenario 3 Inter-Island DC Cable Options with Maui Connection

400 MW DC	Oahu to Molokai
138 kV AC	Molokai to Lanai
2 x 69 kV AC	Lanai to Maui; Molokai to Maui

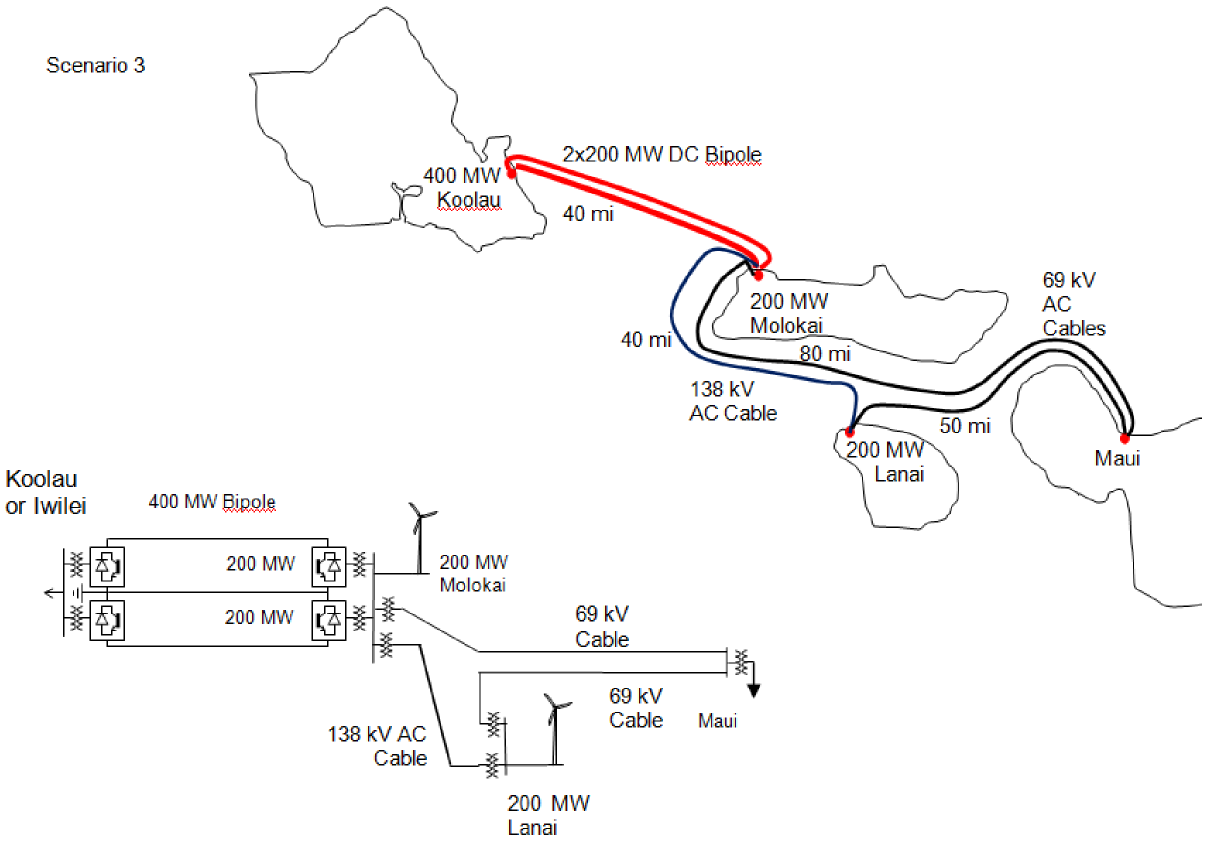


Figure A-7: Scenario 3 with a bipole configuration to Oahu

Control Strategy

The technical performance of Scenario 3 is essentially the same as for Scenario 2. The key factor that is determined from both Scenario 2 and Scenario 3 is the synchronization. The method that is proposed is as follows:

5. Of the two VSC cable feeder poles, one pole must be on an independent clock. This provides the frequency control for the interconnected islands of Molokai, Lanai and Maui. This applies if it is configured with symmetrical monopoles as in Scenario 2. If configured as a bipole as in Scenario 3, both poles could be operated as an independent clock providing they are derived from the same clock.

6. The other VSC cable feeder pole is synchronized through a conventional phase locked loop, which it is able to do through the ac voltage at its terminal connecting busbar at its

sending end. The frequency is defined by the other VSC cable feeder with the independent clock.

7. The VSC feeder with the PLL control has ability to control power. As such it can be automatically scheduled to transmit power equal to the power on the other VSC feeder with the independent clock. In this way they two VSC feeders will equally control the power to Oahu. Alternatively, the power order to the VSC feeder with the PLL controls can be derived from the power from the wind farms and Maui in such a way that losses are minimized and the VSC feeder with the independent clock does not overload.

8. If the VSC feeder pole with an independent clock is faulted and removed from service, then a control mechanism must be in place to ensure the other pole if operating with a phase locked loop, immediately switches to an independent clock. This is not a trivial control action and must be implemented with care and reliability.

When this control strategy is implemented, the power systems and wind farms on Molokai, Lanai and Maui will be synchronized to each other but not to Oahu.

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14. ABSTRACT *(Maximum 200 Words)*

This report provides an independent review included an initial evaluation of the technical configuration and capital costs of establishing an undersea cable system and examining impacts to the existing electric transmission systems as a result of interconnecting the islands.

15. SUBJECT TERMS

undersea cable; Maui; Lanai; Molokai; Hawaii Clean Energy Agreement; grid integration; operational impacts, transmission planning; Electranix; XLPE cable; voltage sourced converters

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