ELECTRANIX

VOLTAGE ANALYSIS OF THE LAMAR DC CONVERTER

Prepared for

Xcel Energy

By

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STUDY PURPOSE STATEMENT

This study was undertaken to examine how the Lamar Dc Converter performs in the power system, both from a voltage control and an operations perspective.

SUMMARY AND CONCLUSIONS

The overvoltages in general fall within the dynamic overvoltage guidelines as specified, with some exceptions. The surge arresters in the dc substation and the nearby ac substations or ac line entrance locations were observed to be rated adequately for the conditions studied.

The operational performance of the dc link was in general satisfactory for normal system configurations. Under some contingency situations, there is requirement for further improvements either in the control or the simulation model if inadequate.

RECOMMENDATIONS

There are a number of control and protection issues for the Lamar Dc Converter that need to be undertaken by Siemens as indicated by the tentative PSCAD model provided by them. It may be that some of these issues have been resolved or need correcting in the model. The issues that need to be addressed are:

1. An ac voltage collapse in the east ac system when power flow is west to east, and with a weakened eastern ac system. A similar problem occurs when the east ac system reverts to a weakened condition from normal while full power is scheduled west to east. (See Section 4.2).

2. A fault on the Boone to Comanche 230 kV transmission line has been observed to cause the back-up protection for the loss of the Boone to Lamar line to incorrectly operate. After the 230 kV line to Boone and to the wind farm have tripped out, the maintenance of the west side ac voltage by the dc link is not very stable. (See Section 4.3).

3. Under conditions of weak east side system, switching of the west side 40 MVAR capacitors on the 53 kV busbar cause disruptive voltage disturbances. (See Section 4.4).

4. Timing of Dc Link recovery after a successful three phase reclose. (See Section 4.8)

5. Ensuring the ac west side voltage control is stable when the Boone to Lamar 230 kV line is out of service. (See Sections 4.3 and 4.8).

6. For a single phase fault on the Boone to Lamar 230 kV line with operation of successful reclosing using the local circuit breaker contacts as indication of line open, there is an apparent delay (100 to 200 msec) before the dc link reduces its power flow to near zero. There is also a period of unstable 230 kV bus voltage control for about 150 msec immediately following the successful reclose. (See Section 4.8)

7. The dc link controls and protections detect ac system faults and configure the dc link to prepare for overvoltages when the fault is cleared. The ac undervoltage associated with this action may be excessively long.

It is recommended that these issues be specifically studied on the upcoming tests of the actual controls and protections on the real time digital simulator (RTDS) at Siemens' facilities in Erlangen, Germany under Customer's Cases. With the configuration used for the ac system on the RTDS, reproduce these cases on PSCAD and adjust the ac system parameters in the RTDS configuration to reproduce the effects on PSCAD as noted above. Then the performance of the dc link on the RTDS using with the actual controls can be compared with what was observed on PSCAD. It is required that for these cases, acceptable performance of the dc link and its controls in real time on the RTDS.

With respect to the switched 345 kV, 50 MVAR line reactor being added at Lamar, it is recommended that it be automatically switched in or out based on sustained overvoltage and undervoltage measured at the 345 kV line end at Lamar with a manual overide.

ACKNOWLEDGEMENTS

The support of Xcel Energy staff with Ernie Poggi was essential for these studies. The assistance of Siemens and Brandt Rashwan Consultants in obtaining the PSCAD models of their design for the Lamar Back-to-Back Dc Link was necessary and appreciated.

1.0 INTRODUCTION

This study was initiated to examine the performance of the Lamar Back-to-Back Dc Converter and how it operated in the electrical power system. The study was started with generic controls and protections using the PSCAD simulation program, but since January 2004, detailed models of the controls and protections supplied by Siemens have been available.

The ac system has been expanded to incorporate an extended system beyond Boone to the west and beyond Finney to the east. In addition, a detailed model of the GE Wind turbine and generators for Colorado Green 162 MW wind farm has been included in the model.

Of concern is how the controls and protections of the Lamar Dc Link perform under contingency and back-up conditions, and with Colorado Green. During the course of the study, several conditions were identified where performance indicated further attention was needed in the design of the dc link and how it performs in the system. These conditions have been shared with Siemens and will continue to be shared with Siemens as they finalize the design of the Lamar Dc Link. It is important that these conditions and issues be dealt with during the real time simulation tests of the controls and protections

Not all possible contingencies have been studied, but it is anticipated that many of the serious operating issues have been identified and dealt with so that when the Lamar Dc Link becomes operational in 2005, there will be few surprises remaining.

2.0 STUDY METHODOLOGY

The PSCAD Version 4 electro-magnetic transient simulation program is used for this study. In order to achieve accuracy in the ac system representation, a suitable model was developed for PSCAD, translated from the WECC and SPP Summer 2005 network models using E-TRAN [9]. The ac system from Comanche and Midway in the west to Lamar is represented in detail and the rest of the WECC is modeled as a true system equivalent network. The eastern ac system from Potter Co to Finney and Holcomb including the Holcomb generator was also represented in detail with a true system equivalent network beyond. 230 kV and 345 kV ac transmission lines in the region of detail were represented as frequency dependent models.

The Lamar Dc Link PSCAD model represents the control and switching sequences that are incorporated in the design that was prepared by Siemens. This combined ac system and Siemens designed dc model provide the best possible simulator needed to evaluate performance of the dc link and ac system.

Various ac system faults are applied to both the east and west ac systems. Where needed, statistical variation of the fault point-on-wave and circuit breaker closings will be undertaken in order to provide a statistical basis. The faults are applied during single contingency conditions to obtain the worst case. The statistical multiple run features of PSCAD are used for the studies.

A severe case for overvoltages occurs when the Dc Link is blocked for one reason or another. The response required of the ac system to minimize the overvoltage consequences of this action by the Dc Link is investigated.

Frequency dependent phase domain travelling wave models are used for all 345 kV and 230 kV lines longer than 15 km, and pi-section models will be used for all shorter lines. The longer lines will be modeled using detailed conductor, ground wire, ground and bundling data.

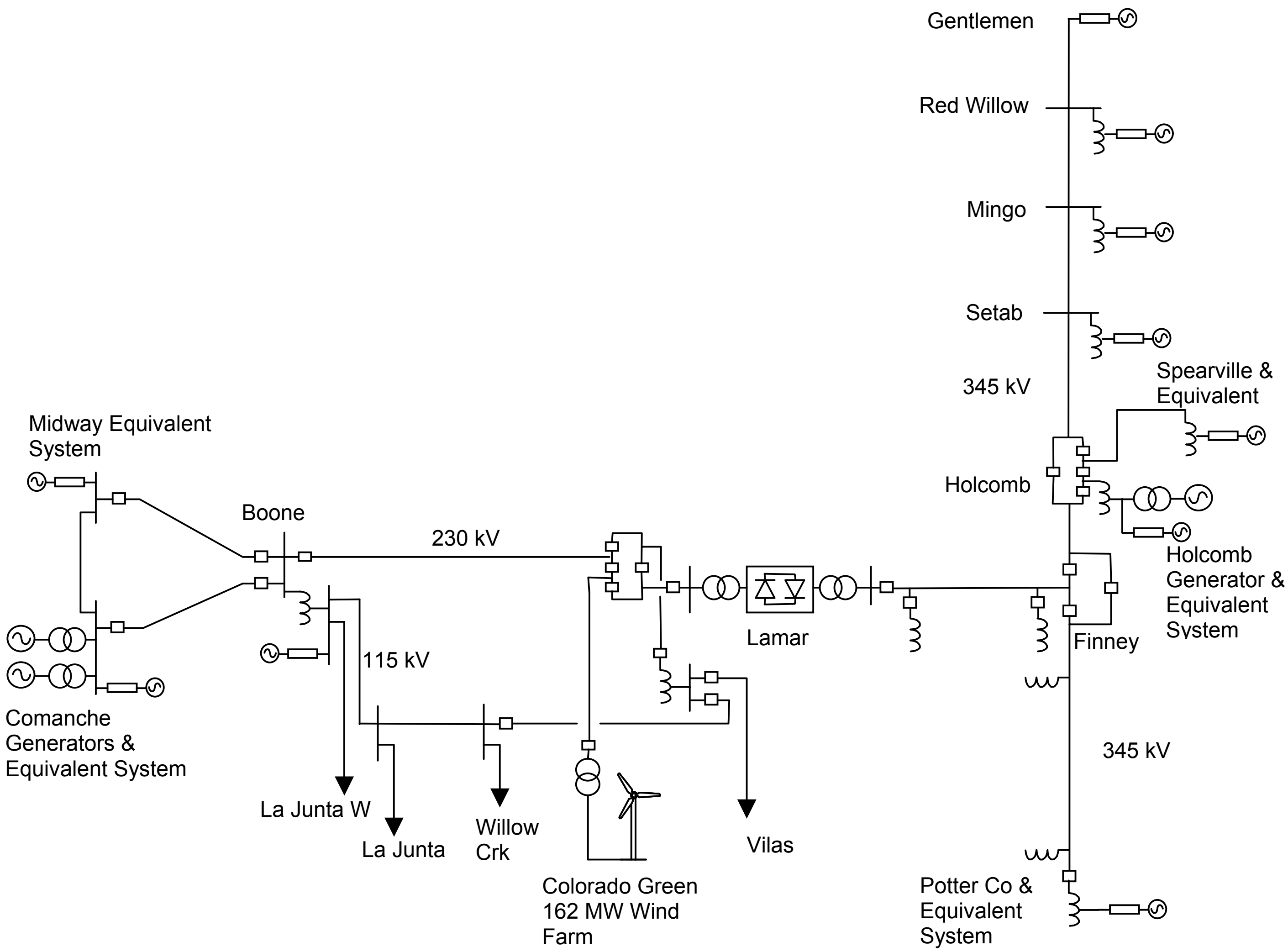


Figure 2.1: Single Line Diagram of the System modelled in PSCAD

- 115 kV Transmission Lines:
  Lamar-Vilas, Lamar-Willow Creek, Willow Creek-La Junta, Boone-La Junta, Boone-La Junta West

  Bergeron travelling wave models are used for all 115 kV lines longer than 15 km, and pi-section models are used for all shorter lines. Data input is from fundamental frequency, positive sequence loadflow data. Zero sequence line impedances are represented but the impedances are approximated. Lines are considered transposed.

- Line Reactors on the Finney – Lamar 345 kV Transmission Line:

  The 50 MVAR line reactor in the Finney – Lamar line connected at Finney is represented as a switched reactor. For most cases, it is considered switched onto the line. A 50 MVAR switched line reactor will also be represented at Lamar end of this line and for most cases is not switched on.

- Transformers:

  Lamar (230/115/13.8), Boone (230/115/13.8), Colorado Green (230/33), Comanche Generator Transformers (230/24).

  Holcomb (345/115), Holcomb Generator Transformer (115/22), Potter County (345/230).

  Transformer models include nonlinear saturation models and delta-tertiary representations (including shunt reactors on the tertiary winding where applicable).

- Back-to-Back Dc Converter at Lamar:

  A model of the 210 MW six-pulse air-core reactor HVDC system is provided by Siemens (including 230/53 kV and 345/53 kV AC Transformers, AC Filters, generic controls with AC Voltage control etc…).

- Wind Farm:

  The latest GE Wind PSCAD models for the Colorado Green wind farm are used for these studies.

  All fault cases are performed initially with the wind generator output at 0.0 MW or the no-wind condition (but the 33 kV system energized, including fixed capacitors on the 33 kV bus). Critical west system fault cases are repeated with the wind at full 162 MW capacity.

- Loads:

  Light system loads are represented.

- Surge Arresters:

  Surge arresters for the 345 kV line end at Lamar and Finney have an MCOV of 220 kV (1.1 pu). Only one bank is represented at Finney.

  The arresters for the high voltage protection of the dc link transformers on both the 230 kV and 345 kV side are specified as Tridelta arresters with an MCOV of 1.05 pu. There are other arresters at Lamar 230 kV side (Ohio Brass 192 kV silicon carbide gapped arresters) that are not represented during the main studies in order to produce worst-case energies and TOV's due to the faults and disturbances.

  For the 53 kV arresters connected phase-to-phase, the MCOV is 57 kV (1.075 pu). The phase to ground arresters on the 53 kV bus are also represented.

- Generators:

  The Comanche generators (COMAN1 and COMAN2) will be represented with exciter, and machine data as per the loadflow/stability data. The DQ0 machine model utilized includes transient, sub-transient and frequency dependent and nonlinear effects.

  The generator at the City of Lamar is not represented as it is not always in service and omitting it will be the worst case in terms of voltage regulation and fault current contribution (as per the HVDC Specification Studies).

  The Holcomb generator is represented in the same detail as the Comanche generators.

  The Colorado Green wind farm is represented at both a no wind condition, and at full load (162 MW) based on a wind turbine/generator model provided by GE Wind.

- System Equivalents:

  To represent the system outside of the study area, a system equivalent is generated based on the data from the loadflow file. The system equivalent contains RL impedances behind voltage sources to ground at all interface busses, and also include impedances (modeled as linear artificial transmission lines or transformers) to represent the off-diagonal coupling between all the interface busses. The system equivalent voltage source terms are calculated so the powerflow in the system (and into the network equivalents) match that from the base case loadflow.

  The E-TRAN program is used to generate the system equivalents and calculate the voltage source terms. PSS/E or PSLF loadflow input files (for both the WECC and SPP systems).

  A good test of the accuracy of the equivalent systems used in the PSCAD systems is to measure the three phase fault current at Lamar 230 kV and 345 kV busses and compare with the maximum short circuit capacities determined previously for the Technical Specification for Lamar Back-to-Back Dc Converter Station, Tables 3.1 and 3.2. The results of the comparison are as follows:

  Table 2.1: Comparison of PSCAD model short circuits with values provided in the Technical Specification for the Lamar Back-to-Back Dc Converter Station.

Short Circuit Location	**From Technical Spec MVA**	**From PSCAD Model MVA**
Lamar 230 kV busbar	637	645
Lamar 345 kV busbar	1238	1100

- Line Fault Detection/Protection Settings and Reclosing Behaviour:

  It is assumed that 345 faults are detected and protective relays open the breakers at each end of the line after 3.0 cycles. The breaker contacts on each phase open at the first current zero after the respective trip signal is received. For closing of a 345 kV line reactor breaker, the time to close is 6.0 cycles.

Three phase reclosing is applied with a 0.5 second reclosing time for the 345 kV line between Lamar and Finney. Single phase reclosing with a 1 second reclose time is applied for the 345 kV transmission line between Finney and Potter County.

It is assumed that 230 kV faults are detected and protective relays open the breakers at each end of the line after 4.5 cycles. The breaker contacts on each phase opens at the first current zero after the respective trip signal is received.

Faults on the 115 kV network are detected and tripped after 6 cycles (again with contact opening at the first current zero).

Three phase reclosing is employed after 0.5 seconds on all 230 kV lines except for the Lamar to Colorado Green 230 kV line (which will not reclose). Reclosing is not performed due to faults on the 115 kV network (ie the breakers will open at each end of the line but will not reclose). The Boone to Comanche line fault was studied both with and without a three phase reclose

3.0 LAMAR – FINNEY 345 kV TRANSMISSION LINE

The issues surrounding the compensation of the Lamar to Finney 345 kV transmission line were studied. The original proposal was to compensate the 345 kV transmission line with a single 50 MVAR fixed line reactor [1]. It was anticipated that load rejection overvoltages under this condition were acceptable so long as there were no contingencies on the eastern power system. If the Finney to Holcomb transmission line section were out of service, it would be necessary to transfer trip the Lamar to Finney 345 kV line immediately following a dc load rejection. To energize the Lamar to Finney 345 kV line when the Finney to Holcomb line section was out of service, it was originally proposed to do so with the 345/53 kV transformer connected, and a 40 MVAR, 53 kV line reactor pre-connected on the its 53 kV busbar [2], [3], [4], [5].

However, Xcel Energy desired to add a second 345 kV, 50 MVAR switched reactor to the Lamar to Finney 345 kV transmission line. This simplified the start up sequencing for Siemens who through the dc link controls, required control of the closing of the 345 kV line end circuit breaker at Lamar. The operational issues of switching the line reactors with the dc link east side 53 kV reactor and capacitor have still to be resolved. One such issue is commutation failure when the line reactor is switched and power flows are west to east.

Another issue is in the switching of this 50 MVAR line reactor in or out depending on whether a sustained overvoltage or undervoltage is detected at the 345 kV line end at Lamar. It is reasonable to automatically switch it in or out based on sustained overvoltage and undervoltage measured at the 345 kV line end at Lamar. 1.06 pu for 30 cycles is suggested for overvoltage detection and 0.94 pu for 30 cycles for undervoltage detection. Such a setting range would allow the east side ac voltage control function of the dc link to operate without significant interference from line reactor switching. A manual override should be provided.

4.0 DC LINK OPERATION

The switching and operational studies undertaken on the ac system to test the performance of the Back-to-back Dc. The issues that were investigated and arose through the course of the study are summarized as follows:

4.1 Insulation Coordination

The surge arresters have been selected for the Back-to-back Dc Link at Lamar [6]. In addition, Xcel Energy has selected high voltage station surge arresters, which include:

Table 4.1: Station surge arresters selected by Xcel Energy

Location of Surge Arrester	MCOV (pu)	Arrester Rating
Lamar 230 KV busbar	1.14	196
Lamar 345 kV busbar	1.1	276

The Tridelta surge arresters selected by Siemens, have a lower MCOV than for the station arresters selected by Xcel Energy. Various faults and disturbances were applied, for normal and contingency operating conditions. Tridelta surge arresters applied are the phase to phase arresters on the 53 kV bus, with an MCOV of 1.075 pu. The Tridelta arresters at the 345 kV transformer on the 345 kV side have an MCOV of 1.05 pu. The manufacturer's switching surge characteristics are modelled in the simulation

A severe case in terms of stress to the surge arresters was a successful reclose on the Lamar to Finney 345 kV line. On the reclose, a significant overvoltage occurred. The surge arresters protecting the 345 kV transformer at Lamar were the most heavily stressed. The summary of peak voltages and arrester energies for this disturbance are in Table 4.2:

Table 4.2: East side peak overvoltages and arrester energy for a reclose fault on the Lamar to Finney 345 kV line.

Parameter Measured	Parameter	Comments
Max rms volts on E 53 kV bus	1.64 pu	These are quite high voltages with the 258 kV arrester on the 345 kV transformer being highly stressed. The high voltages were generated when the reclose occurs.
Max rms volts on Lamar 345 kV bus	1.53 pu	
Max rms volts on Finney 345 kV bus	1.41 pu	
Max rms volts mid line Finney - Potter	1.30 pu	
Max rms volts on Potter Co. 345 kV bus	1.11 pu	
72 kV arrester energy on E 53 kV bus	0.06 kJ/kV	
258 kV arrester energy on 345 kV bus	9.62 kJ/kV	
276 kV arrester energy on 345 kV line end	0.46 kJ/kV	
276 kV arrester energy at Finney 345 kV bus	0.26 kJ/kV	
East side 53 kV F/R/C in service pre-fault	3F, 0R, 1C	

The surge arresters appear adequately rated for the dc converter.

4.2 AC Voltage Collapse and the AC Undervoltage Power Order Reduction (ACUV) Control

Under the contingency condition when the short line section between Finney and Holcomb substations is out of service and power is flowing W→E, a fast voltage collapse was observed as power ramped up to 210 MW. This prompted the inclusion of a fast responding ac voltage collapse detection being incorporated into the operation of the ACUV [7], [8]. This voltage collapse is shown in Figure 4.1, and again in figure 4.2 with the ACUV operating.

Investigation has shown this voltage collapse to be due to the operating features of the Lamar Dc Link. This voltage collapse can also occur when the system is operating normally with 210 MW flowing west to east and the line section between Finney and Holcomb opens up. The east system will go into a voltage collapse as shown in Figure 4.3. The ACUV with its recommended settings does not operate for this disturbance. This then adds to the challenge in determining with settings that will cover the most situations that voltage collapse can occur, yet still discriminating

The ac voltages on both sides of the dc link go into voltage collapse and cyclic recovery with the instigation of the opening of the Finney to Holcomb 345 kV link. The voltage on the west (230 kV) side has a more severe overvoltage than the east (345 kV) side. One consequence of this is that a commutation failure or similar overcurrent occurs as a result of the voltage collapse.

This disturbance is severe enough to cause Colorado Green wind farm to trip off.

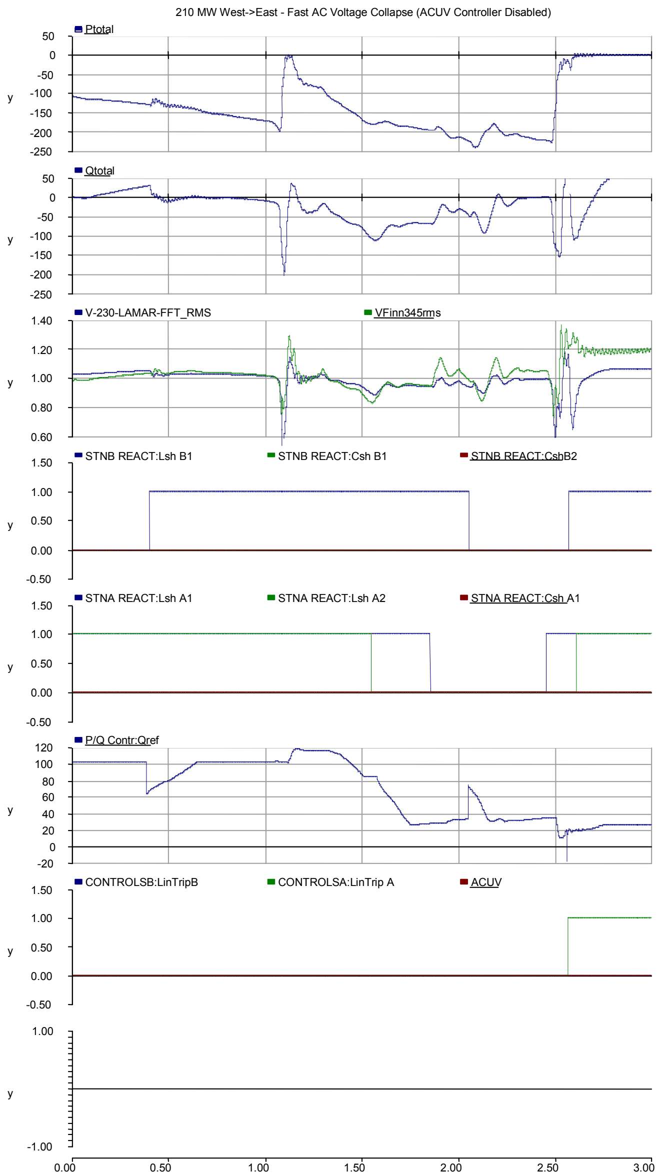


Figure 4.1: Repeated voltage collapse as power W→E attempts to ramp up to full power. 345 kV line Finney to Holcomb out of service. No ACUV in service

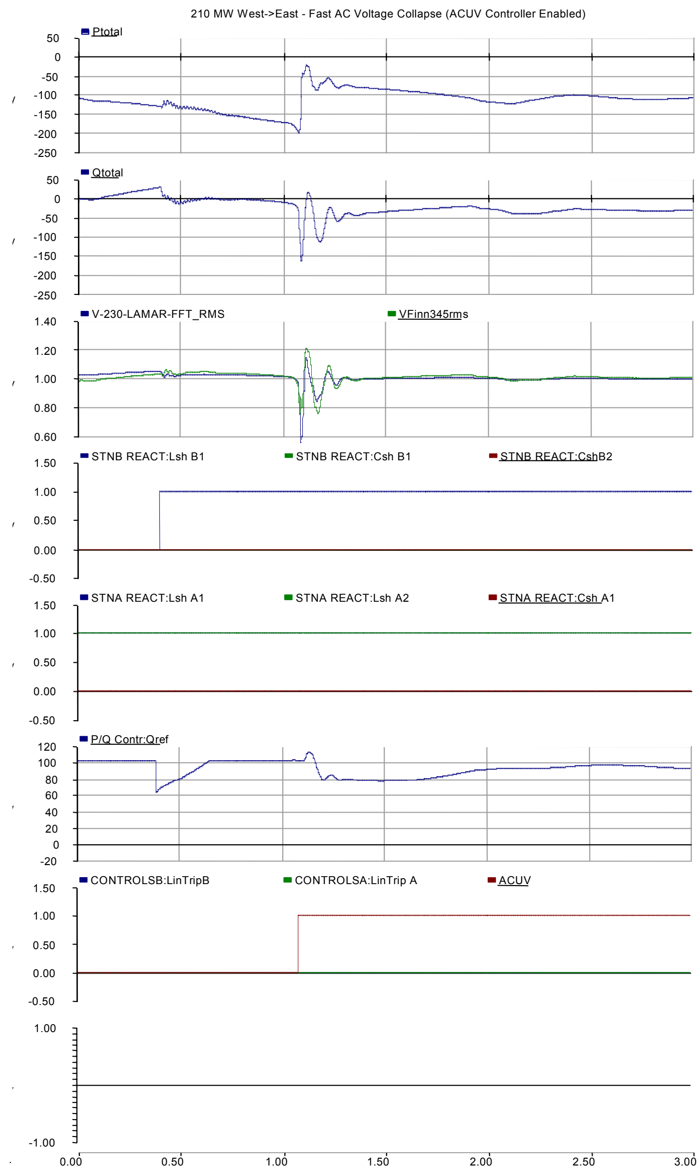


Figure 4.2: voltage collapse as power W→E attempts to ramp up to full power. 345 kV line Finney to Holcomb out of service. ACUV is in service

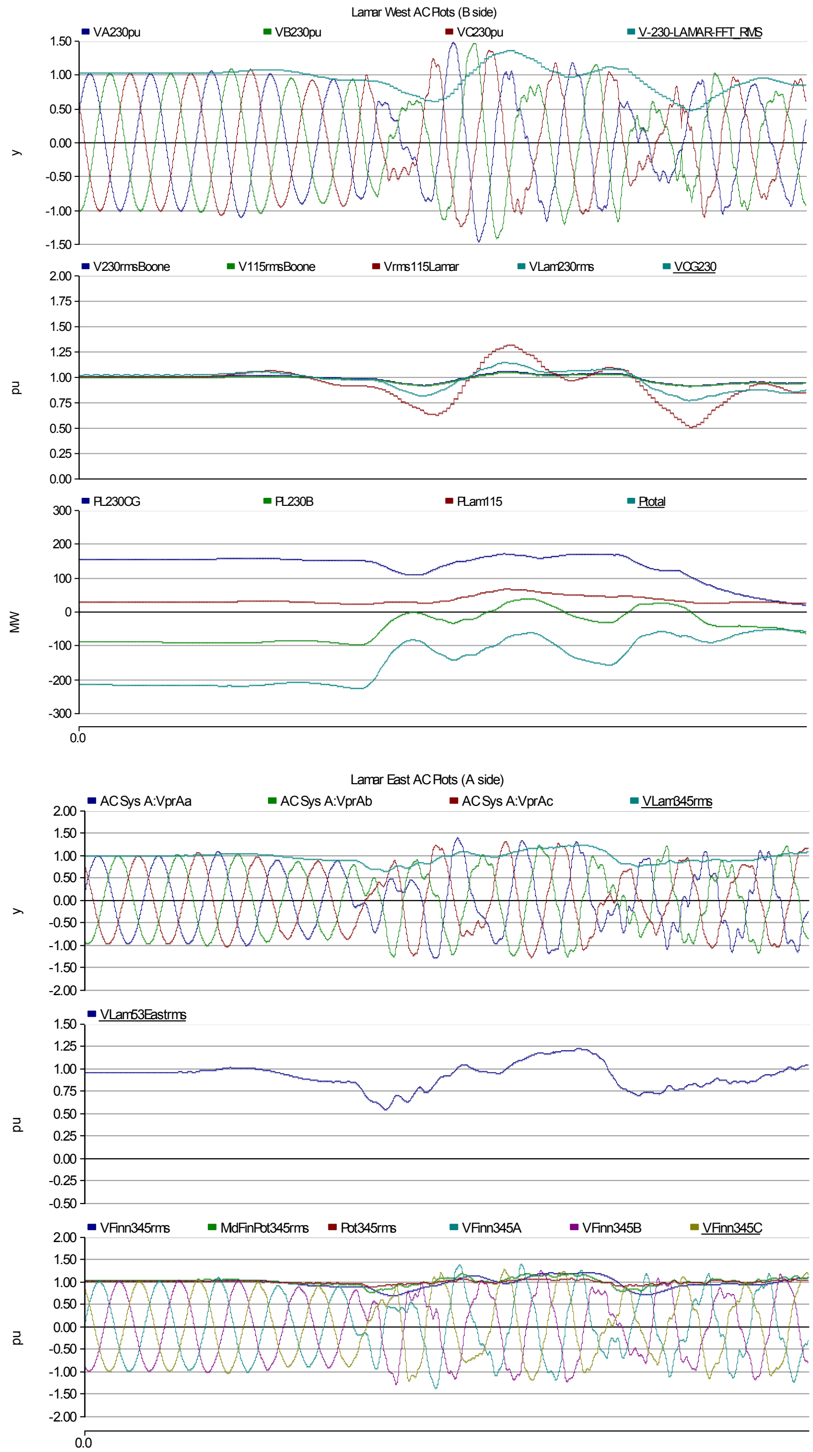


Figure 4.3: The 345 kV line between Finney and Holcomb inadvertently opens while full rated power flows W→E. ACUV is not activated by this disturbance.

4.3 AC Fault on Boone to Comanche Line

The issue here is that a fault on the Boone to Comanche 230 kV transmission line has been observed to cause the back-up protection for the loss of the Boone to Lamar line to operate. In studies of the AC Undervoltage Power Order Reduction controller (ACUV) for the Lamar dc link [7], a false operation of the back-up protection with loss of the Boone to Lamar 230 kV transmission line was observed. This occurred for a permanent fault on the Boone to Comanche 230 kV line.

As a consequence, the Boone to Lamar 230 kV line was tripped by the dc protection when this mode of control in the dc link is invoked. The conditions that applied:

1. Power flow at 210 MW from west to east.
2. Colorado Green wind farm not generating (no wind).
3. Finney to Holcomb 345 kV line and Holcomb generator in service.

The sequence of events that result from this event is as follows:

0 msecs: 1L-G fault on either of Boone to Comanche or Boone to Midway 230 kV lines without reclose. ACUV inhibited.
+80 msecs, the two west side 53 kV bus, 40 MVAR capacitors that were in service switch off.
+95 msecs, the one west side 53 kV bus, 40 MVAR reactor closes in. The ac volts on the Lamar 230 kV bus falls to 0.73 pu and stays there. Dc power falls to 0.71 pu because of the low west side ac volts.
+608 msecs, the Boone to Lamar 230 kV line is tripped at Lamar. Dc power is reduced to near zero. ACUV remains inhibited. Ac voltage control of the west 230 kV bus at Lamar is poorly damped (improved settings required).

These results were observed using the latest preliminary dc link model provided by Siemens. The Lamar 230 kV bus volts observed through this disturbance are as shown in Figure 4.4. The performance of the dc link is shown in Figure 4.5.

A possible signal to inhibit the back-up protection for loss of the Boone to Lamar 230 kV line is to derive it from an impedance or mho relay on the line at Lamar. The phase to ground impedance seen by this relay for this disturbance is plotted in Figure 4.6.

When 3 phase reclosing was applied on the faulted Boone to Comanche 230 kV line, the back-up protection was still initiated for the 0.5 second reclose time, but not for a 0.4 seconds reclose time. This implies the delay times incorporated in the back-up protection should be reset to accommodate the standard 0.5 second reclose time.

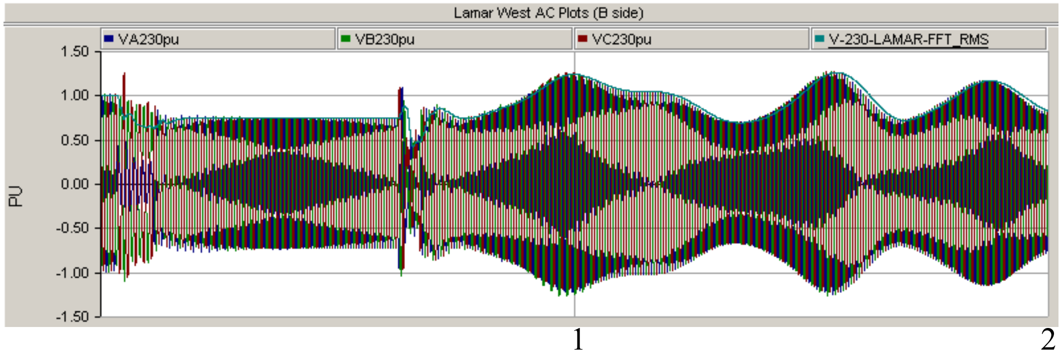


Figure 4.4: Ac volts on the Lamar 230 kV bus following 1L-G fault on the Boone Comanche 230 kV line without three phase reclosing.

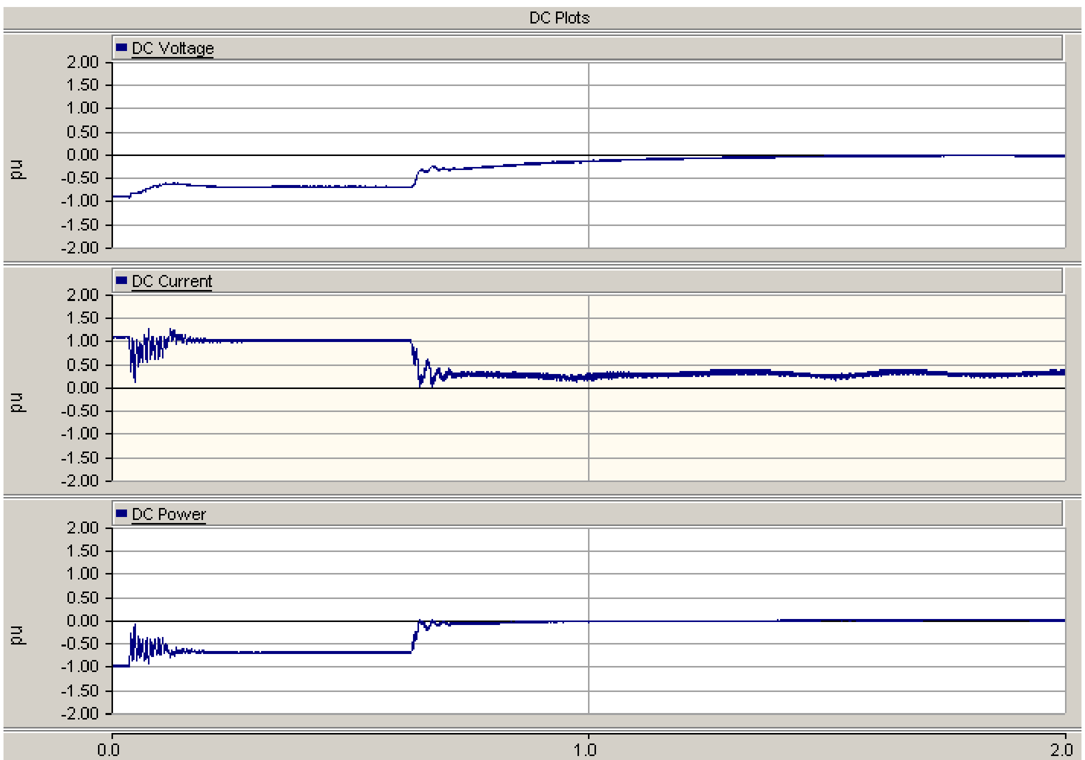


Figure 4.5: Lamar dc link dc voltage, current and power following 1L-G fault on the Boone Comanche 230 kV line with the back-up protection for the tripping fo the Boone – Lamar 230 kV line initiated.

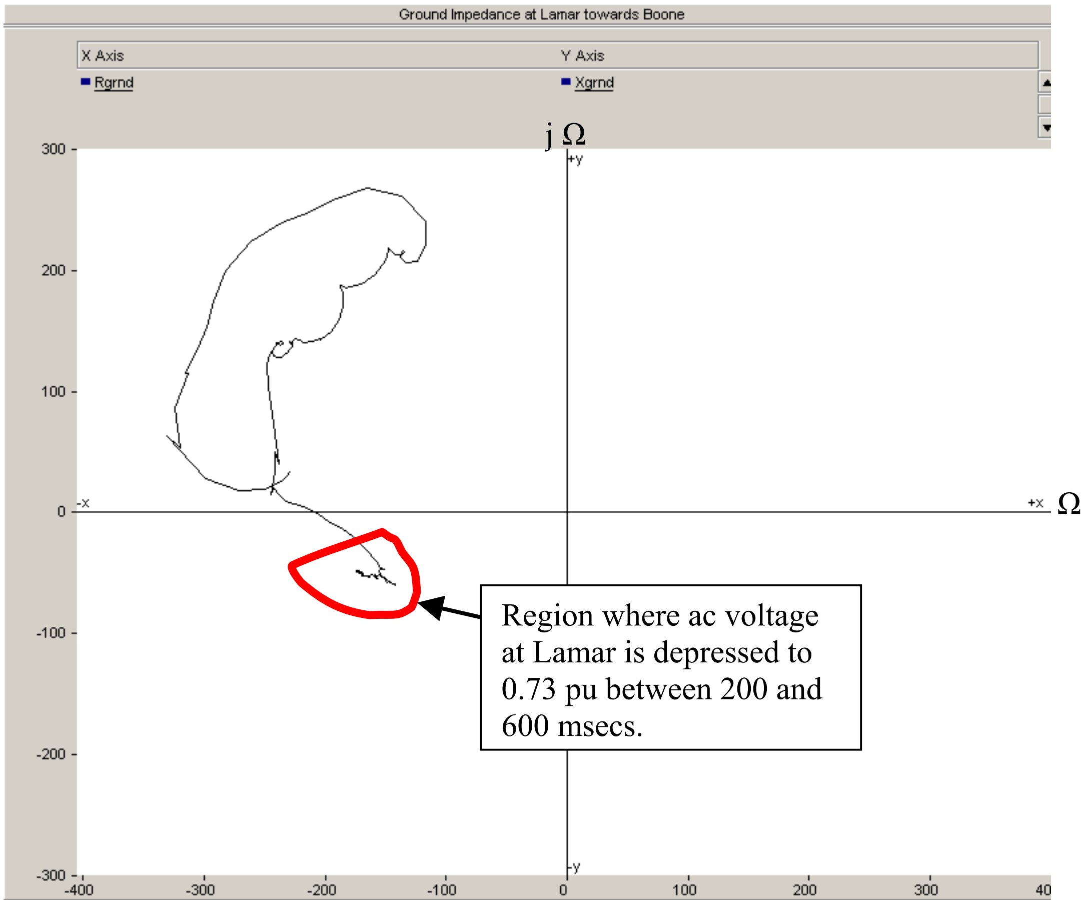


Figure 4.6: Phase to ground impedance plot as seen from Lamar looking to Boone following 1L-G fault on the Boone Comanche 230 kV line.

For the various disturbances, the observed impedances as seen from an impedance relay located on the 230 kV line at Lamar looking to Boone during the period 200 to 600 msec after the disturbances are recorded in Table 4.3:

Table 4.3: Lamar 230 kV impedance relay measurements looking to Boone at 200 msec after fault near Boone is cleared.

Disturbance	Pre-fault Power (MW)	Phase-Ground Impedance Ω	Phase - Phase Impedance Ω	Successful
Steady state operation, no wind	210 W → E	-468 – j113	-544 – j143	√
1L-G Fault Boone-Comanche, no wind, with reclose and no reclose	210 W → E	-143 – j58	-153 – j62	X
1L-G Fault Boone-Midway, no wind, with reclose and no reclose	210 W → E	-180 – j14	-168 – j11	√
1L-G Fault Boone-Comanche, with wind, with reclose and no reclose	210 W → E	-517 – j179	-544 – j121	√
Steady state operation, no wind	105 W → E	-413 – j18	-409 – j19	√
1L-G Fault Boone-Comanche, no wind, with reclose and no reclose	105 W → E	-410 + j55	-420 + j52	√
1L-G Fault Boone-Midway, no wind, with reclose and no reclose	105 W → E	-375 –j22	-377 – j22	√
Steady state operation, no wind	50 W → E	-601 - j41	-601 – j41	√
1L-G Fault Boone-Comanche, no wind, with reclose and no reclose	50 W → E	-603 + j13	-603 +j11	√
1L-G Fault Boone-Midway, no wind, with reclose and no reclose	50 W → E	-700 –j110	728 – j76	√
1L-G Fault Boone-Midway, with wind, with reclose and no reclose	210 W → E	-500 – j170	-491 – j152	√
Steady state operation, no wind	210 E → W	360 – j85	357 – j88	√
1L-G Fault Boone-Comanche, no wind, with reclose and no reclose	210 E → W	237 – j162	234 – j164	√
1L-G Fault Boone-Midway, no wind, with reclose and no reclose	210 E → W	264 – j196	259 – j205	√
Steady state operation, with wind	210 E → W	194 + j2	194 +j2	√
1L-G Fault Boone-Comanche, with wind, with reclose and no reclose	210 E → W	214 – j28	217 – j37	√
1L-G Fault Boone-Midway, no wind, with reclose and no reclose	210 E → W	235 – j46	236 – j47	√
Steady state operation, with wind	105 E → W	281 – j35	282 – j34	√
1L-G Fault Boone-Comanche with wind, with reclose and no reclose	105 E → W	278 – j8	279 – j9	√
1L-G Fault Boone-Midway, with wind, with reclose and no reclose	105 E → W	279 – j41	282 – j41	√
Lamar-Boone line open at Boone	-	73 – j1750	73 – j1750	-

The impedances recorded in Table 4.3 are not fault impedances. Instead, they are what an impedance relay sees at the 230 kV line end looking to Boone from Lamar during the period the back-up protection for the line opening at Boone is waiting to see if a 3 phase reclose is successful. This is a period of about 0.5 seconds.

A possible inhibitor for the operation of the back up protection is if once the back-up protection has been invoked, and if the measured impedance is consistently less than a set level for ≈0.25 seconds during the 0.5 second waiting period, then inhibit the back-up protection from operating.

It may also be possible to detect an open line end at Boone from an impedance relay located at Lamar. The impedance measured would be that of the line charging (approximately 30 MVAR). There is a chance with a condition of no power flowing on the line, and having the Boone 230 kV voltage higher than the Lamar 230 kV voltage, that the relay may observe an apparent impedance similar to an open line end at Boone, but it may not be so. The chance of this happening at any particular instant when a back-up detection is needed, would be quite remote. If this risk is acceptable, then the impedance measurement is another option to consider for invoking the back-up protection for loss of the Boone to Lamar 230 kV line.

The following points can be concluded:

1. The back-up protection on the Lamar dc link for the loss of the Boone to Lamar 230 kV transmission line will have a possibility of being activated for a fault on the Boone to Comanche 230 kV transmission line when power flows are from west to east at or near full load. This will cause the Boone to Lamar 230 kV line to trip unnecessarily, back down the dc power schedule to near zero, and trip out the wind farm.

2. The Colorado Green wind farm if it is operating provides voltage support at Lamar to assist preventing the back-up protection from operating because of a fault on the Boone to Comanche 230 kV line when power flows are from west to east.

3. Successful three phase reclosing on the Boone to Comanche 230 kV line does not prevent the back-up protection from operating. The time delay settings for the back-up protection are not long enough to allow for the 0.5 second three phase reclose to occur. This should be increased by at least 0.05 seconds.

4. The control of ac voltage of the 230 kV busbar when the Lamar to Boone transmission line is out of service and with the loss of the Boone to Comanche line requires improved control gains to provide stable performance.

5. Impedance measurement at Lamar looking to Boone down the 230 kV transmission line could be used to generate a signal to inhibit the back-up protection for faults on and loss of either the Boone to Comanche or Boone to Midway 230 kV transmission lines.

This report highlights a technical issue that needs to be considered in the design of the back-up protection for the loss of the Boone to Lamar 230 kV. No attempt has been made to define a design for such a control as this is Siemens' responsibility. However, some concepts have been identified that might be applied.

4.4 Capacitor Switching on the West 53 kV Busbar

Under conditions of weak east side system, switching of the west side 40 MVAR capacitors on the 53 kV busbar cause disruptive voltage disturbances.

Consider the following condition:

Case Description: Full Power W→E. The 345 kV line to Potter County is out of Service. Colorado Green is in service at 162 MW. The Holcomb generator is out of service.

The Colorado Green wind farm is in full operation. The purpose of this test is to determine whether the wind farm has any impact on the start up of the Dc Link.

As the dc link starts up, two west side capacitors switch in. However, some of the wind turbine generator units were forced to trip off because of the transient voltage caused by the 40 MVAR capacitors switching in on the west side 53 kV busbar. With a stronger east side system, the wind farm units do not trip off.

In Figure 4.7, the top three traces are dc volts, dc current and dc power as the dc link is starting up under this weakened east side condition. It is important to note that a voltage collapse on the east side did not occur in the way it has been observed when the Finney to Holcomb 345 kV line is out of service (Section 4.2 above).

The fourth trace is the power out of the wind farm at Lamar. It can be seen that as each west side capacitor switching occurs, some more wind turbine units switch out.

The last two traces indicate the status of the 40 MVAR mechanical switched capacitors and reactors. The top one is the west (B) side, and the bottom trace is the east (A) side.

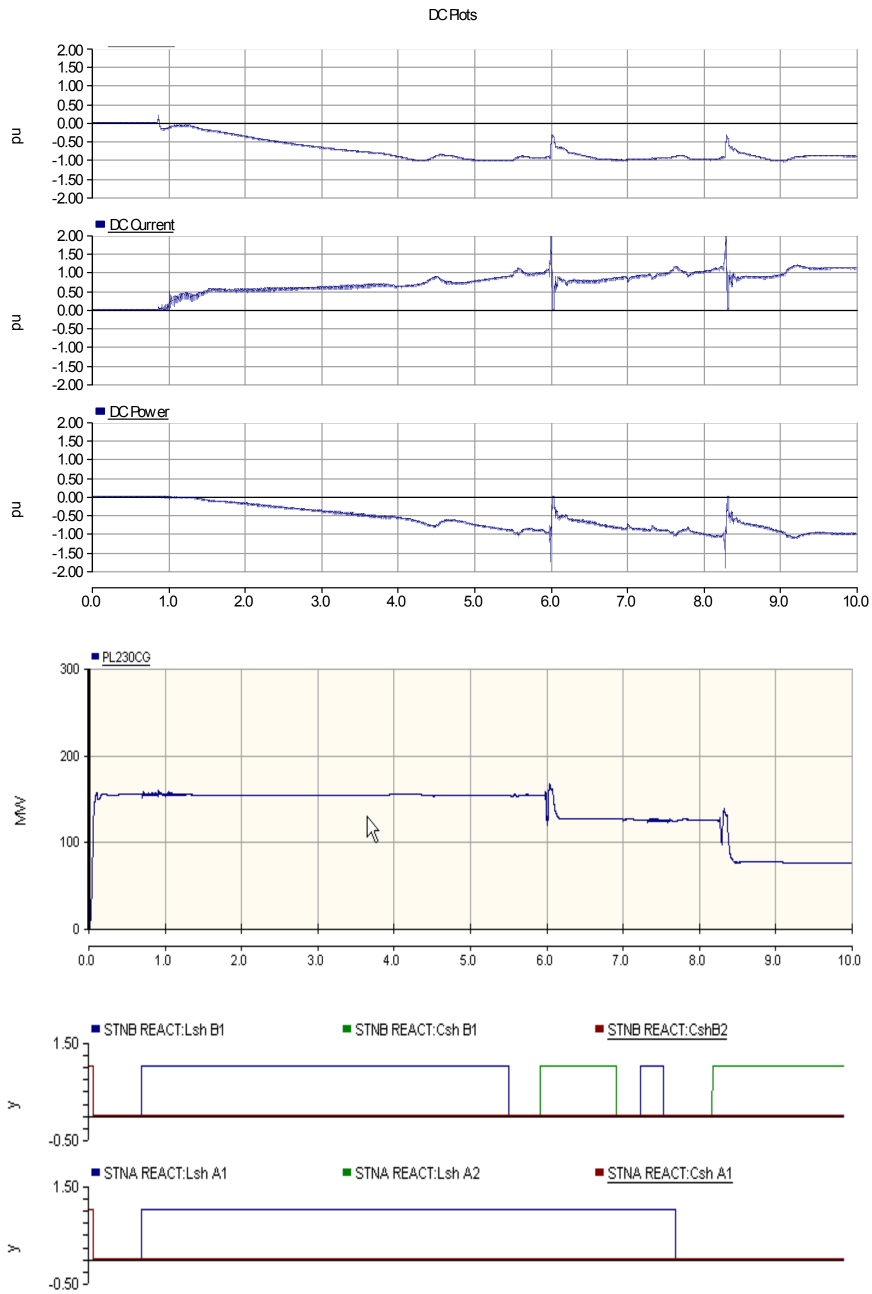
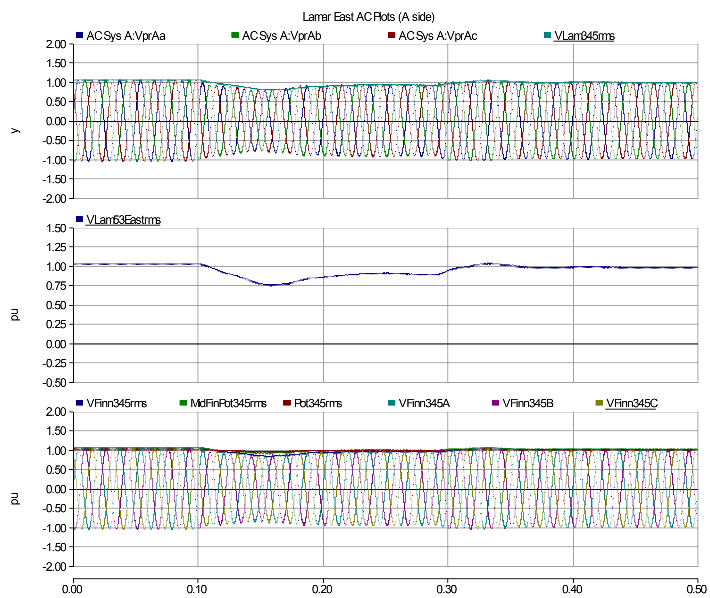


Figure 4.7: Start-up of the dc link with the east side weakened with the Finney to Potter 345 kV line out of service along with the Holcomb generator.

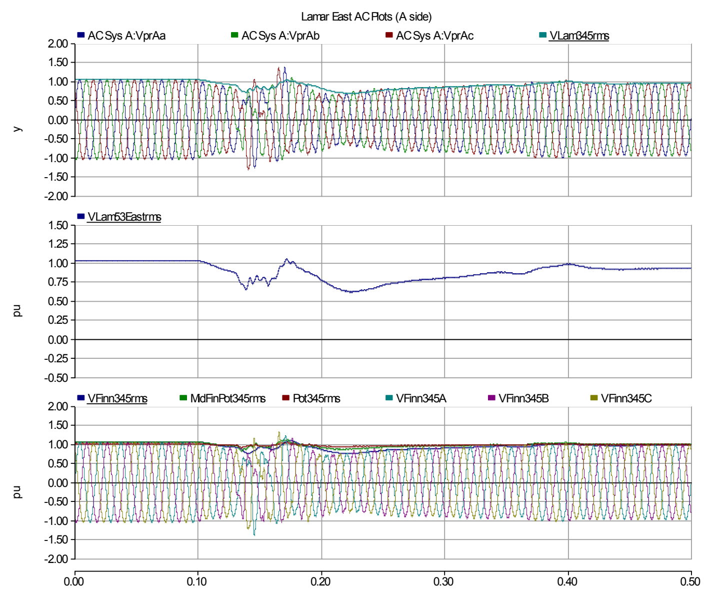
4.5 Switching the 345 kV 50 MVAR line Reactor at Lamar

A main purpose for adding the 345 kV switched 50 MVAR line reactor at Lamar is to limit the ac voltage at Finney and Lamar if the dc link is not operating, and the 345 kV line from Finney to Holcomb is out of service.

With the dc link operating with power flow W→E, the east side converter is operating as an inverter. If the 345 kV switched line reactor at Lamar is closed in while the dc link is operating, a commutation failure may or may not occur, depending on the operating extinction angle of the inverter, and where on the cycle the reactors close in.



No Commutation Failure



Commutation Failure

Figure 4.8: Closing in the 345 kV, 50 MVAR line reactor at Lamar with the east side in a weakened condition and power flows W→E.

The combination of the switching operation and the commutation failure may cause the ACUV to operate, thus resetting the power schedule.

4.6 Timing of Dc Link Recovery on an East Side Three Phase Reclose

The 0.5 seconds for the east side three phase reclose on the Lamar to Finney 345 kV line requires that the timing on the dc link through this sequence needs to be well coordinated.

4.7 Remote AC Line Switching

There are a number of cases where loss of a transmission line is not directly detected by the dc link, and if it continues to operate at its setting, may cause over or undervoltages on the ac power system. This is of concern for some of the following contingencies:

- Loss of the Boone to Lamar 230 kV line.
- With the Boone to Lamar 230 kV line out of service and the dc link operating at minimum power schedule, the loss of a 115 kV line section between Willow Creek and Boone via La Junta.
- With the Finney to Holcomb 345 kV line out, and the Finney to Potter Co. 345 kV line is faulted.

The dc link receives no direct signal of such events, but it has over and undervoltage protection that causes the dc link to block under such conditions if the ac source on either the east or west side becomes isolated.

4.8 Fault on the Boone to Lamar Line, and Successful Reclose

Primary protection causes the dc link to back off during the period the transmission line is open. The power order during the open condition can be set at zero or near zero. During this period the dc link is controlling ac voltage on the west side bus. The wind farm transmission line is tripped at Lamar, whether there is power flowing from the wind farm or not.

The back-up protection also functions but takes time (approx. 0.2 seconds) before the dc link recognizes that the line has opened. During this time the dc link tries to still push power into the 115 kV system for the case when power flow is E→W. As the power increases, the ac voltage at Lamar collapses, failing the dc link, and as it recovers collapses the ac voltage again. When the back-up protection becomes operational, the ac voltage stabilizes. It appears the dc link stays in.

The rate at which the dc power schedule is returned seems quite slow. Further investigation is required to determine if the recovery time can be reduced.

Case Description: Full power E→W. Both the eastern and western systems are intact, including the Holcomb Generator. Colorado Green wind farm is out of service. The Boone to Lamar 230 kV transmission line is faulted with a 1L-G fault, cleared, successfully reclosed after 0.5 second. Primary protection operates.

The results of this case are shown in Figure 4.9 where the 230 kV side volts are shown along with the dc link response. The delay in the dc link power order reduction response after receiving the trip signal of the opening of the Boone line (from breaker contacts) is evident. So to is the period of voltage instability after the phase recloses.

The dc link controls and protections detect ac system faults and configure the dc link to prepare for overvoltages when the fault is cleared. The ac undervoltage associated with this action may be excessively long.

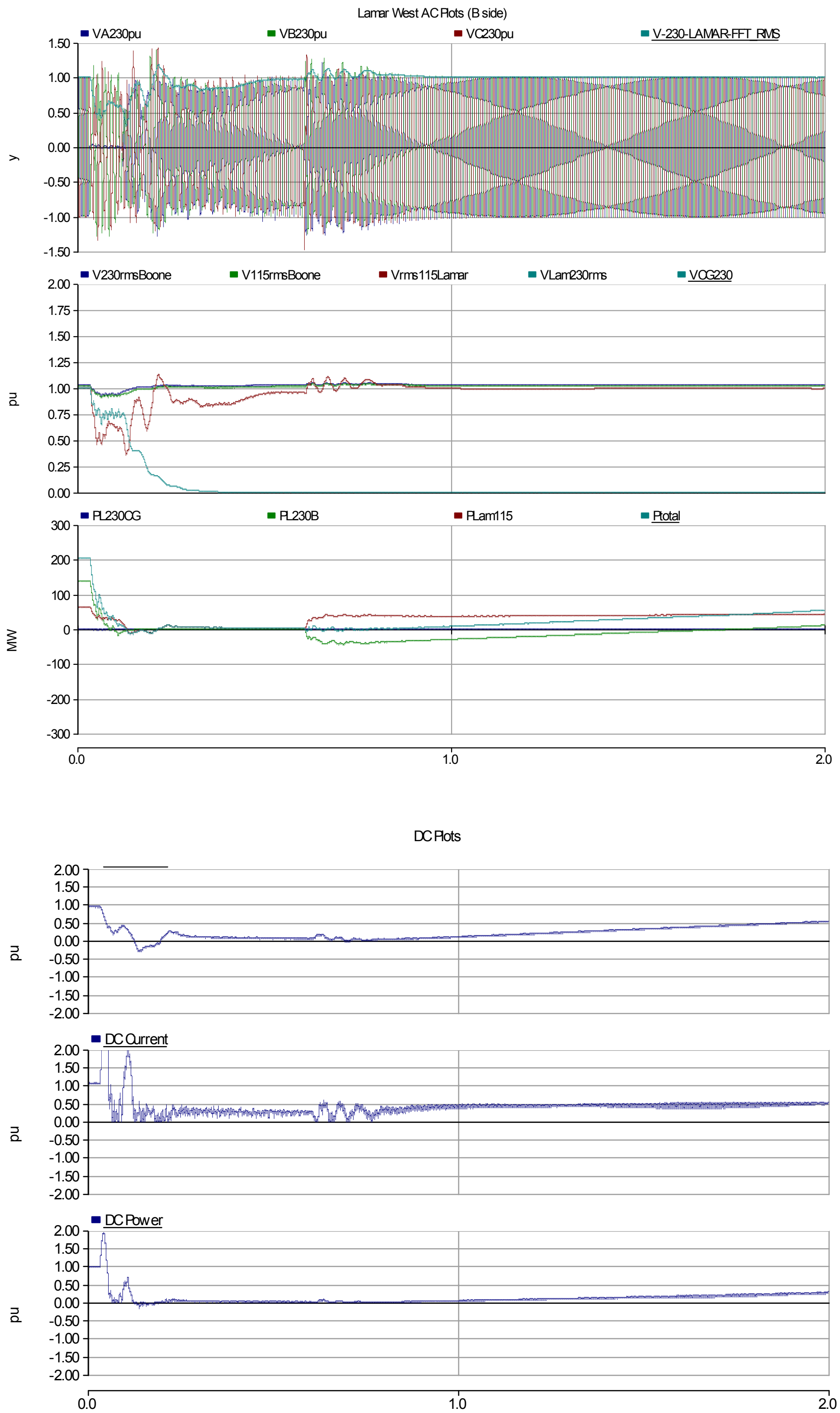


Figure 4.9: Single line to ground fault on the Boone to Lamar 230 kV transmission line, with successful three phase reclosing.

5.0 REFERENCES

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