ANALYSIS OF THE PERFORMANCE OF THE PACIFIC NW-SW STABILITY CONTROL SCHEME DURING THE DECEMBER 22, 1982, BLACKOUT SUMMARY OF PLANNED REVISIONS - RECOMMENDATIONS

by

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INTRODUCTION

On Wednesday, December 22, 1982, at 1629 PST, fierce winds from an arctic storm downed tower 56/232 on Pacific Gas and Electric's (PG&E) 500kV Tesla-Vaca Dixon line. The collapsing tower, falling over laterally, in turn struck down tower 134/529 on PG&E's 500kV Tesla-Table Mountain line, which runs parallel on the same right of way with a 150 foot centerline separation. The failure cascaded when each of the two 500kV lines lost three additional towers and fell across four 230kV and one 115kV lines crossing underneath. These multiple contingency events forced the separation of the Pacific Northwest-Southwest (PNW-SW) area into four major islands. Load shedding schemes within the islands initiated widely scattered blackouts lasting only moments in some areas and up to three and a half hours in others. The total load lost was about 12,200MW, representing approximately 5 million customers.

Scope and Purpose

The scope of this paper extends only to specifics in control and protection. For more details on system generation, abnormal conditions, schedules, etc., before and during the blackout, please refer to the report prepared by the Western Systems Coordinating Council's (WSCC) Operating Practices Subcommittee.[1]

The purpose of this paper is to briefly analyze the performance of PNW-SW control and protection during the blackout, to introduce the planned revisions, and present new ideas which could further enhance performance.

Background of System Stability in the WSCC Service Area

There are some broader aspects of the scene in the WSCC service area one must know to understand the significance of events leading up to large scale blackouts in the Southeast-Southwest regions.

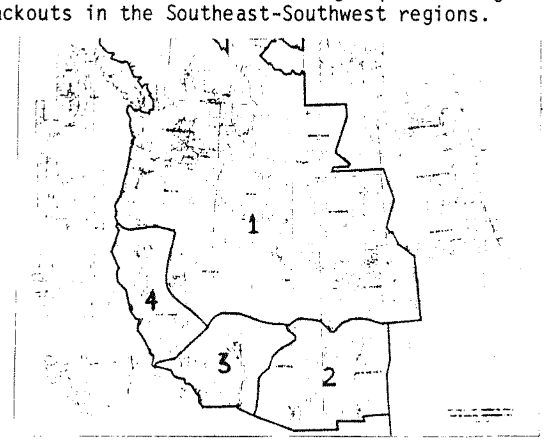

Figure 1
Western System Islanding at 1629 PST.

Please refer to Figure 1, which shows the four major islands that make up the WSCC system.

The majority of large and efficient generating plants (1000 to 6000 MW) are located in islands 1 and 2. With a few notable exceptions, most hydro generators in islands 3 and 4 are small (10-100MW). Larger generating plants are bulk oil or natural gas-fired and are more expensive to operate than coal or hydro plants. To achieve economy in system operation and satisfy environmental restrictions, utilities in islands 3 and 4 are displacing additional oil/natural gas-fired generation with imported hydro and coal-fired generation. It is a reasonable assumption that, by the end of this century, islands 3 and 4 will import from islands 1 and 2 not only the seasonal surplus, but large blocks of firm base power as well.

While the December 22 blackout was initiated by a series of multiple contingency events, future stability studies indicate that during heavy import conditions, we may expect the same results from single contingency events. Specifically, under heavy imports to the SE-SW region, the loss of the PNW-SW Intertie will initiate uncontrolled separation between Arizona and California. This will be followed by a large amount of under-frequency load shedding if no additional control actions are taken.

Description of the PNW-SW Stability Control Scheme Performance Between 16:29:0 and 16:29:02 PST

The PNW-SW Stability Control Scheme performed as designed. However, due to slow multiple contingency events, some of the supervisory functions which were used to enhance security prevented the scheme from initiating fast generator dropping. The reader should refer to Appendix I, which describes the sequence of significant events in detail. Briefly, the PNW-SW Intertie Stability Control Scheme is a combination of several specific purpose logics. One of these logics is designed to detect a "single line loss". The 500kV Vaca-Dixon-Tesla line was not included in this logic scheme. Therefore, when the line faulted and cleared after 2.5 cycles, no further control action was taken. When the second line (the 500kV Table Mountain-Tesla) was relayed 20 cycles later, both single and double line outages were detected by the local logic scheme at Tesla and Table Mountain. At 27 cycles later, BPA's John Day Substation received a "single line loss" signal from Table Mountin via microwave radio (a correct operation). At John Day, the "single line lost" signal is supervised by an AC Power Rate Relay. This relay detected the drop in power on the Intertie 5 cycles after the initial fault occured. It held its output for 18 cycles, waiting for the line-loss signal, then locked out for 72 cycles. When the "single line loss" signal arrived 27 cycles later, the AC Power Rate Relay was locked out and prevented the logic from keying generator dropping and dynamic braking to the Chief Joseph generating plant. After the AC Power Rate Relay reset, the line-loss signal was retransmitted.

The generation was dropped, and the dynamic brake was applied successfully at Chief Joseph on the second power swing at 100 cycles.

The "double line loss" microwave signal from Table Mountain was delayed 55 cycles before it reached BPA's Grizzly Substation due to the slow operation of the microwave transfer trip scheme. At Grizzly, the "double line loss" signal is also supervised by an AC Power Rate Relay. This relay detected the loss of power on the Intertie 2 cycles after the initial fault occured. It held its output for 33 cycles waiting for a signal, then locked out for 72 cycles. When the "double line loss" signal finally arrived 55 cycles later, the rate relay was locked out and prevented the logic from keying fast generator dropping. After the AC Power Rate Relay reset, the signal was retransmitted 144 cycles later. This time generator dropping was successful. Chief Joseph Dam dropped 840MW, John Day dropped 760MW, Rocky Reach and Wells Dam 360MW. The signal at Four Corners which separates the SE from the NE was received from Grizzly at 147 cycles.

<u>Analysis of the PNW-SW Stability Control Scheme Performance Between 16:29:0 and 16:29:02 PST</u>

Initial investigation was focused on the performance of the AC Power Rate Relay, which supervises the PNW-SW System Stability Logic (SSL) at BPA's John Day and Grizzly substations. Originally, the SSL was designed to detect the loss of a "double line" by detecting the positions of the breaker "b" switches. The AC Power Rate Relay was developed to provide security and directional discrimination between heavy import/export conditions. "Double line" loss of the PNW-SW Intertie during heavy export conditions to the SW involves large power changes ($-\Delta P/\Delta t \geq 1000$MW/80msec) plus the trip signal from the "b" switch logic. Note that these two events are essentially simultaneous. When the SSL requirements were extended to detect "single line loss" far within the California System, the AC Power Rate Relay had to be set very sensitive ($-\Delta P/\Delta t \leq 300$MW/80msec); as a result, the relay now had the tendency to operate during normal load switching.

In order to enhance the SSL security, a "window" was added to the AC Power Rate Relay logic. The window essentially required that the AC Power Rate Relay operation be followed by a trip signal from a "b" switch logic within 18 cycles. If the trip signal was not received, the AC Power Rate Relay would block the SSL scheme for 1.2 seconds. In the last ten years this strategy has been very successful. The SSL scheme was secure, did not false trip, and had many correct operations.

The December 22, 1982 sequence of events were the slow evolving type, and an excellent example for relay engineers of the way nature (through multiple contingency) can defeat even the most carefully designed protection scheme. Briefly, when the initial fauls occurred on the 500kV Vaca-Dixon-Tesla line, the line loss was detected by the AC Power Rate Relays. However, this line's PCB "b" switch logic was not included in the SSL scheme. The "b" switch logic trip signal indicating "double line loss" came 27 cycles later, when the 500kV Table Mountain-Tesla line faulted and cleared. Since the two signals were more than 20 cycles apart, the "window" of the AC Power Rate Relay delayed high-speed generation dropping and dynamic braking for 1.2 seconds (144 cycles).

While the preliminary investigation targeted the performance of the AC Power Rate Relay, more detailed post mortem analysis determined that the delayed operation was not a significant factor leading to the large scale blackout.

The performance of the underfrequency load shedding scheme in the SE-SW regions was more significant. This subject will be discussed in more detail below.

<u>Summary of Planned Revision to the PNW-SW Stability Control Scheme.</u>

The following improvements are in progress:

1. The Grizzly and John Day AC Power Rate Relays that supervise signals from PG&E have been reset to eliminate the relay lockout time.

2. The communication time has been shortened and reliability increased for sending a signal between Tesla and Grizzly. This was accomplished by eliminating the supervision of the signal at intermediate substations.

3. Action has been initiated to replace the backup scheme (97 RC relay) at Four Corners with a redundant signal from PG&E's Midway and Round Mountain stations which initiates the NE/SE separation.

4. PG&E will install a redundant microwave system between Tesla and Round Mountain by 1984 to improve reliability.

5. A new out-of-step controller which operates on the rate of change of apparent resistance augmentation (R&$\dot{R}$) has been developed by BPA and it is now under evaluation.[4] This relay may prevent Intertie separation for single contingency disturbances such as the loss of a power plant in the SW.

The above modifications will provide a much more reliable separation scheme between the NW-SW and the NE-SE.

<u>Discussion</u>

Prior to the disturbance, the PNW-SW Intertie power flow to northern California was 2685 MW. Soon after the Intertie was lost, the Southern California-Nevada/Arizona ties were tripped on Out-of-Step (OS), representing an additional loss of approximate 3300MW. Other simultaneous events where control and protection schemes shut down generating units, false-tripped power lines, etc., tended to further aggravate the situation but did not alter the fundamental problem within the WSCC service area. Briefly stated, the WSCC system depends on the transfer of large blocks of power from one region to the other over long distances through a few major Interties. The WSCC system must have high-speed generator dropping at the sending end accompanied by high-speed load shedding on the receiving end in order to stay balanced when a major tie is lost. A limited amount of high-speed load shedding will prevent OS conditions and the subsequent loss of the remaining ties. This in turn will prevent loss of load on a much larger scale. Underfrequency conditions usually occur only after all the major tie lines are lost; therefore, the existing underfrequency schemes can not be relied upon to avert large scale blackouts.

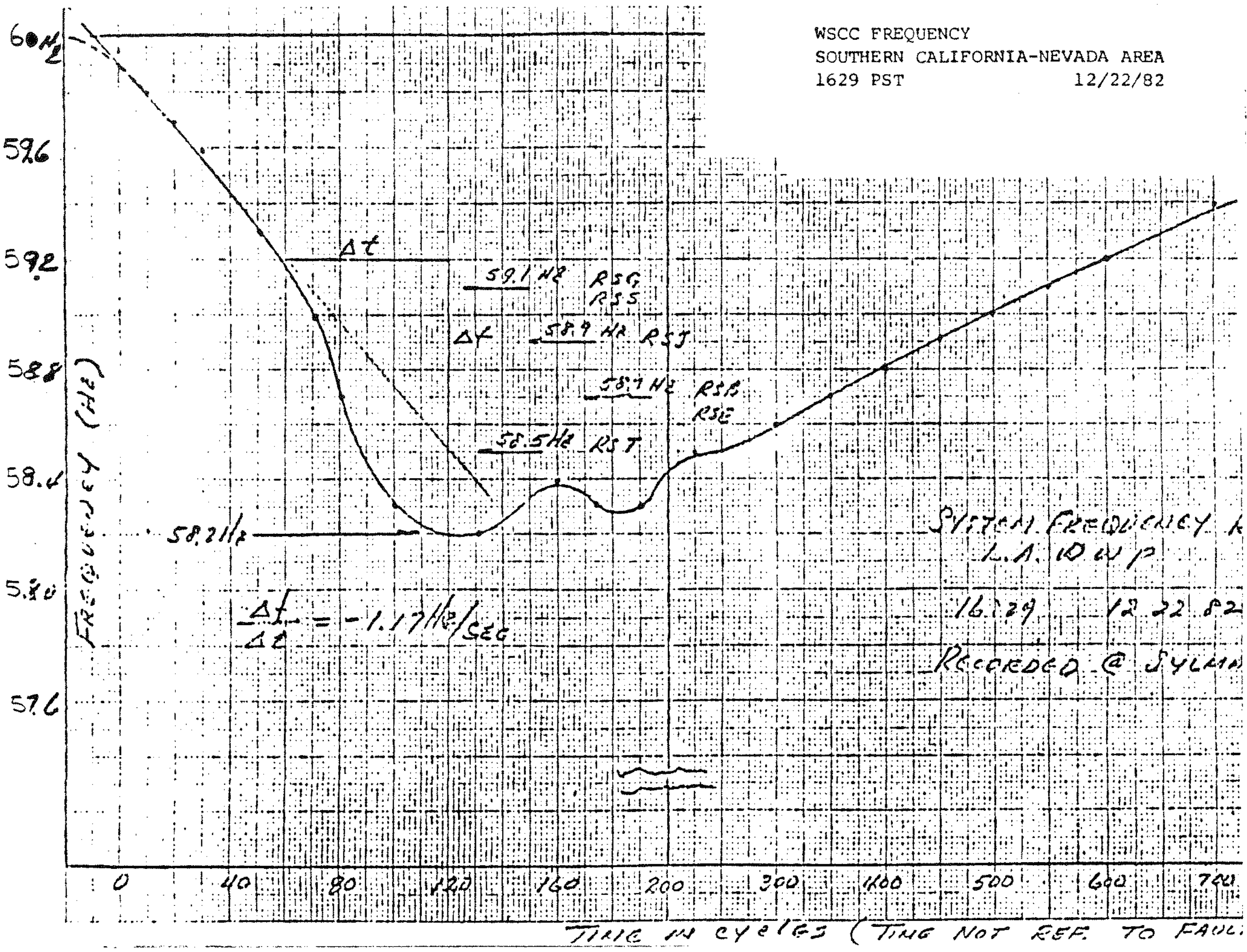

Figure 2

WSCC Frequency. Southern California-Nevada at 1629 PST.

Underfrequency Load Shedding

The advantages of underfrequency-type load shedding are many. Two examples are low cost and simplicity of scheme. The author is well aware that many utilities throughout the world rely on such schemes for their primary protection during system disturbance and have been very successful. One reason for their success is that in most systems' frequency tends to decline on a relatively gentle slope. This permits the proper timing coordination between blocks of load to be shed. The underfrequency load shedding program of the Southern California-Nevada system, for example, was coordinated on a -0.4Hz/sec. rate of change of frequency. Please refer to Figure 2 which depicits actual rate of frequency decline in the Southern California-Nevada region measured at Sylmar at 1629 PST.

The rate of change of frequency was -1.17Hz/sec., bottoming at 58.2Hz. Some areas were as low as 57.8Hz. It is beyond the scope of this paper to discuss the response of thermal generating units, boiler feed pumps, and other rotating machinery when the frequency collapses at an exeptionally high rate below 58.5Hz. Most relay engineers are familiar with the subject and there are many papers available. However, to achieve economy in system operation, the utilities are planning to increase the Interties' power limit. Under such conditions, the loss of one Intertie followed by the loss of the other interties due to OS conditions, could produce even larger $-\Delta f/\Delta t$ and lower bottom frequencies in the California-Nevada Region if no additional control actions are taken.

High-Speed Load Shedding

There are definite technical problems associated with high-speed load tripping schemes in the California region. System studies indicate that between 1000 to 1500 MW of load shedding would be required within 10 cycles to prevent OS conditions on the remaining tie lines. There are no large electric furnace type loads in the region which can be shed. The design engineer, therefore, is faced with a difficult problem of dropping many small loads over a large area. Sending a coded message over TV channel(s), cable TV, AM-FM Radio, or PLC are but five interesting possibilities.

CONCLUSION

Transient stability criterion of the PNW-SW Intertie is based upon the Intertie withstanding a major single contingency type of disturbance like a three-phase fault near a large generating plant.

Statistical data within the WSCC service area indicates that single contingency three-phase faults are practically nonexistant, while double and triple contingency events are more common. For example, the probability of having another fault on the 500kV Tesla-Vaca Dixon line followed by a simultaneous trip of the 500kV Tesla-Table Mountain line due to relay misoperation and the subsequent loss of the Arizona-New Mexico ties due to an out-of-step condition -- essentially the same sequence as the December 22 events -- is much higher than a three-phase bus fault at the Grand Coulee Dam. Events leading up to the blackout prove that, in most instances, underfrequency load shedding will not avert large scale blackouts in the California-Nevada region. The recommended improvements described serve only to improve the reliability of the separation scheme between the NW-SW and the NE-SE. High-speed generation dropping in the PNW, combined with high-speed load tripping in the SW, is an effective way to quickly balance demand with available supply and limit blackouts to a relatively small area when the PNW-SW Intertie is lost.

REFERENCES

(1) WSCC System Disturbance Report for the 500 kV Pacific Intertie Separation at 1629 PST. on December 22, 1982. Prepared by WSCC Formal Review Committee, February 1983.

(2) Summary of Stability Control Systems Used in the Pacific Northwest. Prepared by BPA's Branch of Substation and Control Engineering, October 1, 1979.

(3) Proposed Summer 1983 Increase in Pacific AC Intertie Power Limit to 3200MW, May 31, 1983.

(4) "New Out-of-Step Relay with Rate of Change of Apparent Resistance Augmentation," Taylor, Haner, Hill, Mittelstadt, Cresap. IEEE July 1982, 82SM445-5.

APPENDIX I

SIGNIFICANT SEQUENCE OF EVENTS (12,22,82 at 1629 PST)

ELAPSED TIME (Cycles)

0 Vaca-Tesla 500kV line relayed by BØ ground fault, cleared in 2.5 cycles.

2 Grizzly power rate relay picked up. Drop out is delayed for 33 cycles, then locks out for 1.2 seconds.

5 John Day power rate relay picked up. Drop out is delayed for 18 cycles, then locks out for 1.2 seconds.

20 Table Mountain-Tesla 500kV line relayed by AØ ground fault, cleared in 2.5 cycles.

27 John Day received Table Mountain single line loss signal. Chief Joe brake and generator drop signal not sent because the John Day power rate relay was locked out.

29 Vaca Dixon 500/230kV Transformer Bank #11 tripped due to 500kV double line outage relay scheme.

30 Table Mountain 500/230kV Transformer Bank tripped due to 500kV double line outage relay scheme. Separates CDWR Hyatt-Thermalito and PG&E Upper Feather River generation.

55 Grizzly received Round Mountain double line loss separation signal. Separation signal to Four Corners and to PP&L at Malin and generator dropping signals not sent because Grizzly power rate relay was locked out.

56 Round Mountain 500/230kV Transformer Bank tripped due to 500kV double line outage relay scheme.

73 Malin-Meridian 500kV line relayed due to overvoltage.

79 Pit-Vaca #1 230kV line relayed by distance relay.

85 Cottonwood-Vaca Dixon #1 230kV line relayed by distance relay.

89 Cottonwood-Vaca Dixon #2 230kV line relayed by distance relay.

91 Pit-Vaca Dixon #2 230kV line relayed by distance relay.

93 Four Corners-Pinto 345kV line relayed by an unexplained relay operations trip at Pinto with a transfer trip to the Four Corners terminal.

95 Tesla-Stagg 230kV line relayed by AØ ground fault.

97 McCullough-Victorville #2 500kV line relayed by relay misoperation.

106 Chief Joe brake on.

107 Malin-Meridian 500kV line reclosed.

112 Malin-Meridian 500kV line tripped from Meridian overvoltage.

113 McCullough-Navajo 500kV line relayed by out-of-step relay.

114 Navajo units initiated sequential shutdown.

116 El Dorado-Moenkopi 500kV line relayed by out-of-step relay.

124 Palo Verde-Devers 500kV line relayed on out-of-step condition Zone 1.

126 Liberty-Mead 345kV line relayed by out-of-step relay.

129 El Dorado-Mohave 500kV line relayed by out-of-step relay.

129 El Dorado-Lugo 500kV line relayed by out-of-step relay.

135 Rio Oso-Tesla 230kV line relayed by BØ ground fault.

136 Glen Canyon Unit 7 relayed by overcurrent relay.

142 Midpoint-Malin 500kV line tripped by Grizzly transfer trip while carrying 610 MS. PP&L Jim Bridger Plant dropped 512 MW.

Grizzly power rate relay sent generator drop to Chief Joe, PP&L trip to Malin, generator drop to John Day, trip to Four Corners, trip to Round Mountain, generator drop to Wanapum, Rocky Reach, and Wells.

143 Glen Canyon-Sigurd 230kV relayed by distance relay.

144 Grizzly transfer trip signal received at Four Corners.

Chief Joe dropped 840 MW, John Day dropped 760 MW, Rocky Reach dropped 240 MW, and Wells dropped 120 MW. Wanapum was set to drop 240 MS, but failed due to microwave trip problems.

147 Four Corners-Shiprock 230kV line tripped by Grizzly transfer trip.

Shiprock-San Juan (PSNM) 230kV line tripped at Shiprock.

Galleogos (PSNM) 115kV tie to the City of Farmington relayed by Grizzly transfer trip.

152 Table Mountain transformer bank #1 lightning arrestor failed causing a BØ ground fault.

154 Glen Canyon 345/230kV tie tripped by Grizzly transfer trip.

Bellota-Tesla #1 and #2 230kV lines relayed by distance relay.

172 Mead-McCullough-Boulder 230kV line relayed by distance relay.

173 The PP&L 500kV circuit switches on the Malin 500/230kV Transformer Bank tripped by PP&L trip from Grizzly.

176 Malin-Round Mountain #1 500kV line relayed at Round Mountain by overvoltage.

179 Malin-Round Mountain #1 500kV line relayed by transfer trip at Malin.

Cottonwood-Elverta #2 and #3, and Keswick-Cottonwood #2 and #3 230kV lines relayed by distance relay completing islanding of PG&E Area #3.

USBR Shasta-Trinity generation separated.

Hurley-Tracy #1 and #2 230kV lines relayed by distance relay.

Malin-PP&L overvoltage relay tripped the Malin-Round Mountain #2 line at Malin.

Bellota-Gregg #1 and #2 230kV lines relayed by distance relay completing the islanding of PG&E Area #4 and Feather River-Stanislaus hydro.

180 Ranch Seco Power Plant unit separated.

181 Malin-Round Mountain #2 500kV line relayed at Round Mountain due to transfer trip from Malin.

194 Midway-Vincent #1, #2, and #3 500kV lines relayed, separating PG&E and SCE, due to underfrequency.

515 Grizzly-Round Butte 500kV line tripped at Grizzly to transfer trip from Round Butte.

Time

1630 Round Mountain-Cottonwood #1 and #2 230kV lines relayed at Round Mountain. PG&E Pit River generation separated.

Midway-Wheeler Ridge #1 and #2 230kV lines relayed at Midway by underfrequency.

1631 Cottonwood-Humboldt #1 and #2 115kV lines relayed, islanding PG&E Area #2.

1632 Moss Landing Unit #7 separated due to boiler feedpump trouble.

San Mateo-Martin 230kV relayed completing islanding of PG&E Area #5.

1643 Glen Canyon Unit #7 on line.

1645 Round Mountain 230kV bus reenergized from Pit River generation.

1650 CDWR Hyatt-Thermalito generation reparalleled.

1653 Parker-Gene 230kV tie relayed.

1655 PG&E Sub-Island #3 paralleled with Sub-Island #1.

1656 Hoover 230kV Unit A-3 on.

1700 Glen Canyon-Sigurd line in service.

1702 Southern Californiz-Southern Nevada paralleled with Arizona when Moenkopi-El Dorado 500kV line was closed.

1711 PG&E Area #5 paralleled with Area #1.

1717 Lugo-Mohave 500kV line energized. Power to Mohave restored.

1720 McCullough-Victorville 500kV line energized.

Navajo-McCullough 500kV line energized.

1722 Palo Verde-Devers 500kV line energized.

1732 Mead bus sectionalizing PCB's closed parelleling WAPA-WALC with SCE and NPC.

1734 Boulder-Mead-McCullough 287kV line energized.

1744 Northern California paralleled with

Southern California when Midway-Vincent #2 500kV line was closed.

1750 PG&E Sub-Island #2 paralleled with Sub-Island #1, #3, and #5.

1803 Arizona paralleled with Rocky Mountain area when Four Corners-Pinto 345kV line was closed, restoring all major islands.

1811 PG&E Sub-Island #4 paralleled with Sub-Island #1, #2, #3, and #5.

1833 Four Corners-Shiprock 230kV line energized.

1834 Shiprock-San Juan 230kV line energized.

1836 Malin-Round Mountain #2 500kV line energized.

1847 Pacific NW and PG&E paralleled at Round Mountain.

1850 Round Mountain-Table Mountain #2 500kV line energized.

1856 Round Mountain-Table Mountain #1 500kV line energized.

1857 Table Mountain-Vaca 500kV line energized.

1859 Vaca 500/230kV transformer in service.

1900 Pacific NW and PG&E 230kV line overloads due to loop flow with two 500kV lines out of service north of Tesla.