ANL/DIS-13/10



Simulation of the Secondary Frequency Control Capability of the Advanced PSH Technology and Its Application to the SMUD System

Decision and Information Sciences

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

Availability of This Report
This report is available, at no cost, at http://www.osti.gov/bridge. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

ANL/DIS-13/10

Simulation of the Secondary Frequency Control Capability of the Advanced PSH Technology and Its Application to the SMUD System

prepared for
U.S. Department of Energy – Wind and Water Power Technologies Office

prepared by
Vladimir Koritarov
Decision and Information Sciences, Argonne National Laboratory

James Feltes and Yuriy Kazachkov
Siemens PTI

November 2013

This page intentionally left blank.

Contents

Preface

This report is one of several reports developed during the U.S. Department of Energy (DOE) study on the “Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the United States.” The study is led by Argonne National Laboratory in collaboration with Siemens PTI, Energy Exemplar, MWH Americas, and the National Renewable Energy Laboratory. Funding for the study was provided by DOE’s Office of Energy Efficiency and Renewable Energy (EERE) through a program managed by the EERE’s Wind and Water Power Technologies Office (WWPTO).

The scope of work for the study has two main components: (1) development of vendor-neutral dynamic simulation models for advanced pumped storage hydro (PSH) technologies, and (2) production cost and revenue analyses to assess the value of PSH in the power system. Throughout the study, the project team was supported and guided by an Advisory Working Group (AWG) consisting of more than 30 experts from a diverse group of organizations including the hydropower industry and equipment manufacturers, electric power utilities and regional electricity market operators, hydro engineering and consulting companies, national laboratories, universities and research institutions, hydropower industry associations, and government and regulatory agencies.

The development of vendor-neutral models was carried out by the Advanced Technology Modeling Task Force Group (TFG) led by experts from Siemens PTI, with the participation of experts from other project team organizations. First, the Advanced Technology Modeling TFG reviewed and prepared a summary of the existing dynamic models of hydro and PSH plants that are currently in use in the United States. This summary is published in the report *Review of Existing Hydroelectric Turbine-Governor Simulation Models*. The review served to determine the needs for improving existing models and developing new ones.

Although the existing dynamic models for conventional hydro and PSH plants allow for accurate representation and modeling of these technologies, there was a need to develop dynamic models for two PSH technologies for which, at present, there were no existing models available in the United States. Those two technologies are (1) adjustable speed PSH plants employing doubly-fed induction machines (DFIMs), and (2) ternary PSH units. The Advanced Technology Modeling TFG developed vendor-neutral models of these two PSH technologies, and they are published in two reports: (1) *Modeling Adjustable Speed Pumped Storage Hydro Units Employing Doubly-Fed Induction Machines*, and (2) *Modeling Ternary Pumped Storage Units.*

Extensive testing of newly developed models was performed using the Siemens PTI’s standard test cases for the Power System Simulator for Engineering (PSS®E) model, as well as the Western Electricity Coordinating Council’s (WECC’s) modeling cases for Western Interconnection that were provided in PSS®E format. The results of model testing are presented in the report *Testing Dynamic Simulation Models for Different Types of Advanced Pumped Storage Hydro Units*.

In addition to the project team members and DOE, all of these reports have been reviewed by the AWG members, and their comments and suggestions have been incorporated into the final versions of the reports. Parts of these reports will also be included in the final report for the entire study to illustrate the model development component of the work.

This page intentionally left blank.

Acknowledgements

The authors would like to acknowledge the support and guidance provided to the project team by the staff and contractors of the DOE/EERE's Wind and Water Power Technologies Office (WWPTO), including Michael Reed, Rajesh Dham, Charlton Clark, Rob Hovsapian, Patrick O'Connor, Richard Gilker, and others. The authors are also grateful to the members of the Advisory Working Group for their excellent collaboration and efforts in advising the project team and guiding the study. The Advisory Working Group included a broad spectrum of global pumped storage hydropower specialists, including the following:

Michael Reed, Rajesh Dham, Charlton Clark, Rob Hovsapian, Patrick O'Connor, Richard Gilker	DOE/EERE – Wind and Water Power Technologies Office (WWPTO)
Rachna Handa	DOE – Office of Electricity Delivery and Energy Reliability (OE)
Rahim Amerkhail	Federal Energy Regulatory Commission (FERC)
Michael Manwaring, Douglas Divine	National Hydropower Association (NHA)
Mark Jones, Elliot Mainzer	Bonneville Power Administration (BPA)
Xiaobo Wang	California Independent System Operator (CAISO)
Zheng Zhou	Midwest Independent System Operator (MISO)
Matt Hunsaker	Western Electricity Coordinating Council (WECC)
Tuan Bui	California Department of Water Resources (CDWR)
David Harpman	Bureau of Reclamation (Reclamation)
Kyle L. Jones	U.S. Army Corps of Engineers (USACE)
Scott Flake, Greg Brownell	Sacramento Municipal Utility District (SMUD)
Paul Jacobson, Stan Rosinski	Electric Power Research Institute (EPRI)
Alan Soneda	Pacific Gas and Electric Co. (PG&E)
Osamu Nagura	Hitachi Mitsubishi Hydro
Teruyuki Ishizuki	Toshiba Corp.
Rick Miller, Rick Jones	HDR Engineering Inc. (HDR|DTA)
Jiri Koutnik, Maximilian Manderla	Voith Hydro
Christophe Nicolet	Power Vision Engineering (PVE)
Peter McLaren	Center for Advanced Power System (CAPS)
Landis Kannberg	Pacific Northwest National Laboratory (PNNL)
Klaus Engels	E.ON Wasserkraft GmbH
Kim Johnson	Riverbank Power
Steve Aubert, Le Tang	ABB Switzerland Ltd.
Ali Nourai	DNV KEMA

This page intentionally left blank.

Acronyms and Abbreviations

ACE	area control error
AGC	Automatic Generation Control
AS	adjustable speed
AWG	Advisory Working Group
DFIM	doubly-fed induction machines
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
PSH	pumped storage hydro
PSS®E	Power System Simulator for Engineering
RF	regulating factor
SMUD	Sacramento Municipal Utility District
TFG	Task Force Group
UCE	Unit Control Error
WECC	Western Electricity Coordinating Council
WI	Western Interconnection
WWPTO	Wind and Water Power Technologies Office

Units of Measure

Hz	Hertz
kV	kilovolt(s)
min	minute(s)
MVA	megavolt-ampere(s)
MW	megawatt(s)
sec	second(s)

This page intentionally left blank.

Executive Summary

The Sacramento Municipal Utility District (SMUD), as a typical balancing authority and project team member, was suggested by the Advanced Technology Modeling TFG for testing the models of the advanced pump storage hydro technology newly developed in the course of the DOE project and for demonstration of the potential benefits of this technology.

Based on the 2017 Summer Peak Load Western Interconnection (WI) case, an equivalent was created comprising the full model of SMUD connected to a single machine equivalent of the WI system, with all of the 230 kV tie lines to the WI retained. All machines of the SMUD system were retained, including the hydro units of the Upper American River hydro plants.

The dynamic simulation model of the Automatic Generator Control (AGC) was updated to add the capability to control not only conventional generating units whose prime movers are simulated by standard PSS®E turbine-governor models but also the newly developed models of the advanced pump storage hydro units.

Taking into consideration the size of the WI interconnection, the frequency deviation occurring as a result of a large load or generating unit turning on or off is relatively small. Hence, from the two components of the AGC area control error (ACE), namely frequency and intertie power flow, the latter component can be considered as the major criterion of AGC performance quality.

A list of disturbances used to demonstrate AGC performance included the following:

- Drop of generating units of different sizes in SMUD
- Ramping down of the generation in SMUD
- Ramping up of the generation in SMUD.

The two latter disturbances can be construed as representing a change in renewable power (e.g., a drop or an increase in wind or solar generation power).

The following scenarios in terms of SMUD hydro units have been considered:

- All conventional hydro turbines (present condition)
- All conventional hydro turbines plus two conventional pumps
- All conventional hydro turbines plus two adjustable speed (AS) pumps
- All conventional hydro turbines plus two ternary pumps in hydraulic short-circuit mode of operation.

The proposed Iowa Hill pumped storage hydro plant was also added to the SMUD system. Its three AS PSH units were tested as pumps for two WI system conditions, namely the 2017 summer peak load case and 2022 light load case. Wind power ramping up from zero to 400MW was used as a disturbance.

For all of these scenarios and disturbances, the newly developed models of AS PSH units and ternary units showed expected performance and allowed demonstration of the expected advantages of the advanced PSH technology, specifically the capability of AS pumps and ternary pumps to participate in secondary frequency control (AGC).

Section

1

Introduction

In the framework of the U.S. Department of Energy (DOE) sponsored project, “Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the United States,” new dynamic simulation models were developed to represent advanced pumped storage hydro (PSH) technologies. The models developed include the following:

- An adjustable speed PSH unit employing a doubly-fed induction machine (DFIM) in the:
  - Generator/turbine mode of operation
  - Motor/pump mode of operation
- A ternary PSH unit in the:
  - Turbine mode of operation
  - Pump mode of operation
  - Mixed (hydraulic short circuit) mode of operation

Previous reports [1, 2, 3] described these technologies and gave a detailed description of the models. Another report [4] described the testing of the models. That report also demonstrated the control capabilities of these technologies.

An imbalance between load and generation in interconnected systems results in deviations of tie flows and frequency. The response of the power controls to restore these quantities to their pre-disturbance values is split between primary frequency control and secondary frequency control. Primary frequency control is performed by the turbine governors. The capabilities of the advanced pumped storage hydroelectric technologies to contribute to primary frequency control were demonstrated in the reports referenced above. However, these technologies also have the ability to contribute to secondary frequency control (also often referred to as automatic generation control [AGC]). This report contains additional simulations results that demonstrate these capabilities and illustrate how these models can now be used in analysis required for investigations into applications of these technologies.

1.1 The Sacramento Municipal Utility District (SMUD)

The Sacramento Municipal Utility District (SMUD), as a typical balancing authority and a member of the project advisory group, was suggested by the Advanced Technology Modeling Task Force Group (TFG) as an appropriate example system to be used for testing of the models of the advanced PSH technology developed in the course of the DOE project and demonstration of the potential benefits of this technology.

SMUD's service area is about 900 square miles and covers primarily Sacramento County, California. Its peak demand was 3,299 megawatts, and its generation is a mix of natural gas–fired plants and hydroelectric generation plants. The hydro power plants are primarily the plants of the Upper American River Project[1] shown in Figure 1-1. The SMUD bulk transmission system[2] comprises 230 kV and 115 kV lines, as shown in Figure 1-2.

Section 2 describes the modeling of the SMUD system.

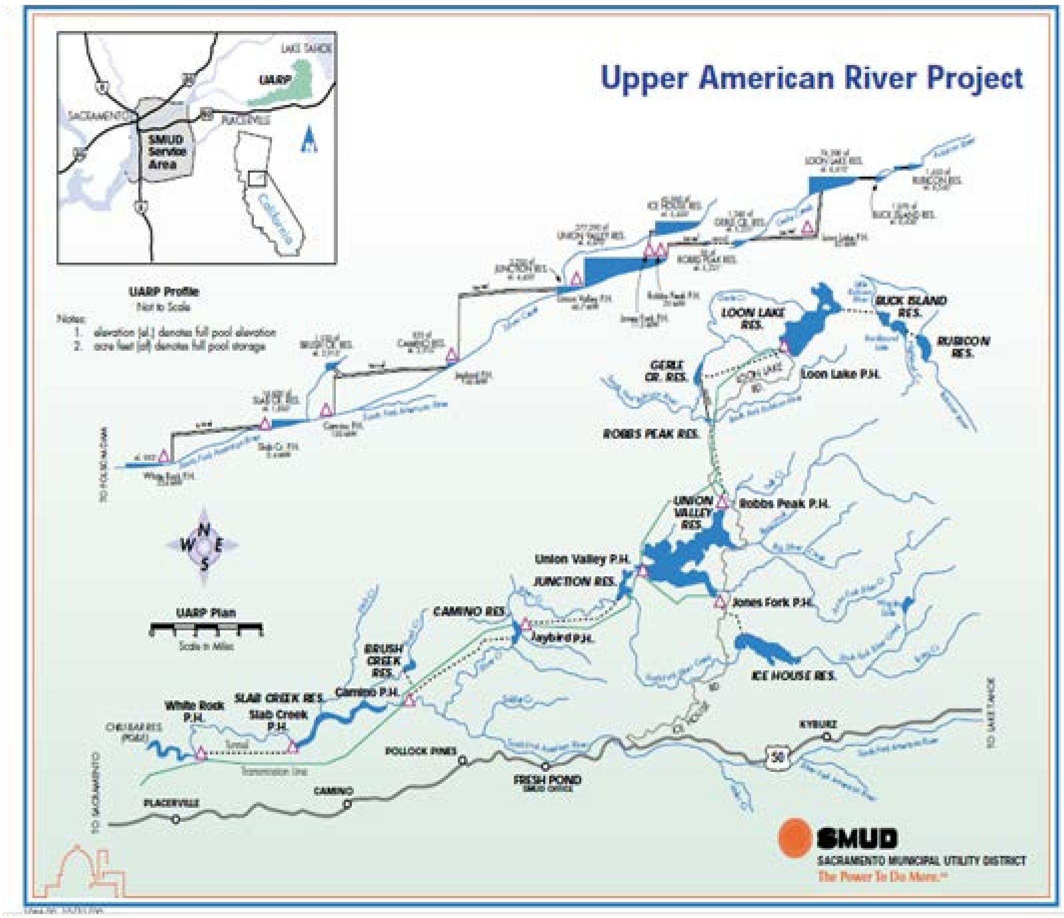


Figure 1-1. Upper American River Project

---

[1] Sacramento Municipal Utility District's Upper American River Project (FERC NO. 2101), Application for New License, Exhibit A, Project Description, Sacramento Municipal Utility District, Sacramento, California, June 2005.
[2] Ibid.

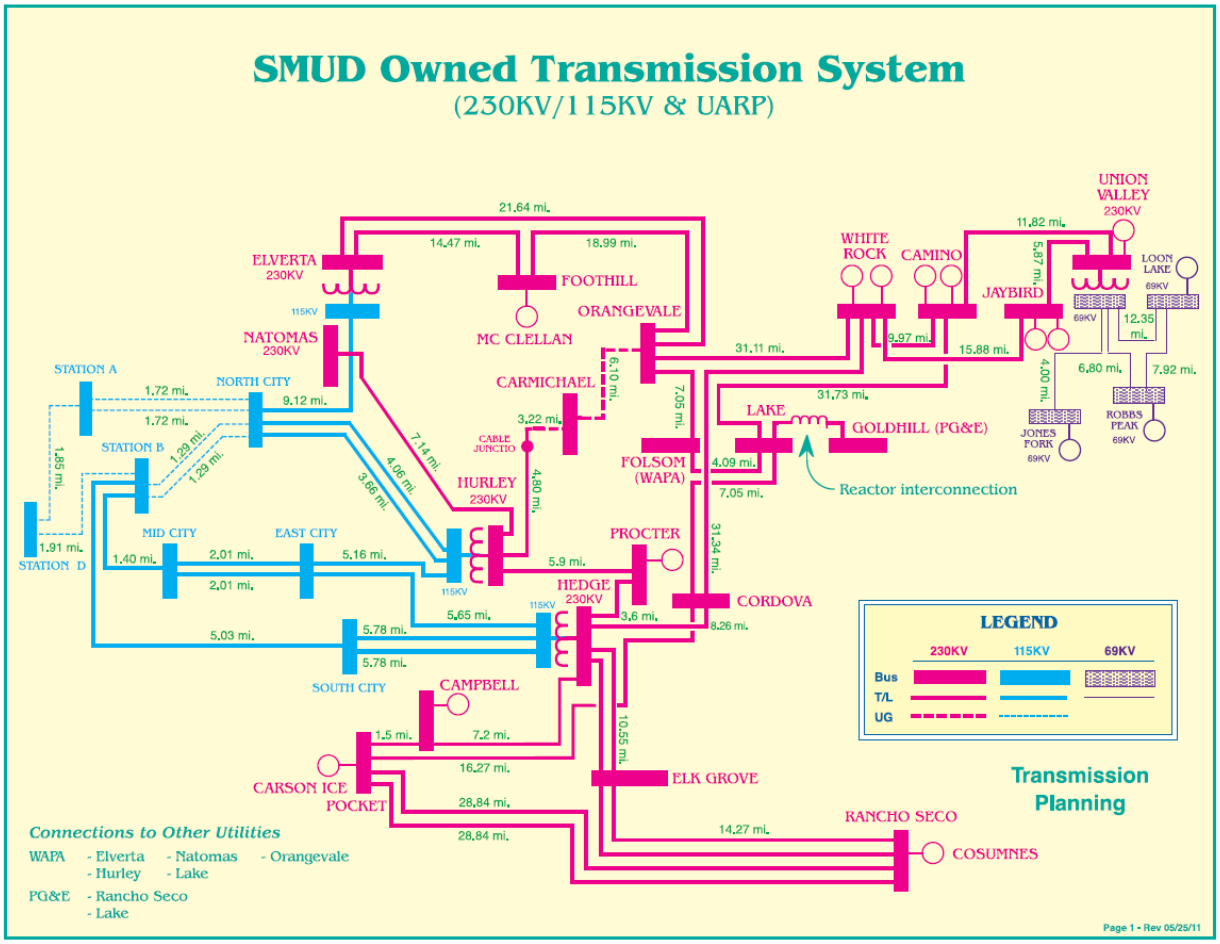


Figure 1-2. SMUD Transmission System

This page intentionally left blank.

Section

2

Equivalent of the SMUD System

The power flow and dynamics data for the SMUD system was based on a 2017 Western Electricity Coordinating Council (WECC) system model. In WECC's 2017 summer peak load case, SMUD is represented by zone 322 with the totals shown in Table 2-1:

Table 2-1. SMUD Area Totals (WECC Zone 322)

```
                 Zone 322 SMUD

     Generation      Loads    Net interchange
MW      1235.0        3072.0      -1859.9
MVAR     182.5         580.8        346.3
```

There are twelve 230 kV ties from SMUD to the WI delivering 1859.9 MW from the outside world to SMUD loads, as follows (Table 2-2):

Table 2-2. Line Flows on the 12 SMUD 230 kV Ties (flow direction from SMUD to other WECC areas)

```
FROM ZONE  322

   TO ZONE  305
   X---- FROM ZONE BUS ----X   X----- TO ZONE BUS -----X
     BUS# X-- NAME --X BASKV     BUS# X-- NAME --X BASKV  CKT       MW       MVAR
    37012 LAKE        230.00   30337 GOLDHILL    230.00*  1     -106.7      39.9
   TOTAL FROM ZONE  322 TO ZONE  305                            -106.7      39.9

   TO ZONE  311
   X---- FROM ZONE BUS ----X   X----- TO ZONE BUS -----X
     BUS# X-- NAME --X BASKV     BUS# X-- NAME --X BASKV  CKT       MW       MVAR
    37016 RNCHSECO    230.00*  30500 BELLOTA     230.00   1     -166.4      39.0
    37016 RNCHSECO    230.00*  30510 CAMANCH     230.00   2     -161.4      41.2
   TOTAL FROM ZONE  322 TO ZONE  311                            -327.8      80.2

   TO ZONE  325
   X---- FROM ZONE BUS ----X   X----- TO ZONE BUS -----X
     BUS# X-- NAME --X BASKV     BUS# X-- NAME --X BASKV  CKT       MW       MVAR
    37005 ELVERTAS    230.00   37520 OBANION     230.00*  1     -251.9      25.3
    37005 ELVERTAS    230.00   37546 ELVERTAW    230.00*  1     -157.4      42.2
    37010 HURLEY S    230.00*  37546 ELVERTAW    230.00   1      -67.7      25.1
    37010 HURLEY S    230.00*  37546 ELVERTAW    230.00   2      -70.6      24.6
    37010 HURLEY S    230.00*  37585 TRCY PMP    230.00   1     -224.1      35.1
    37010 HURLEY S    230.00*  37585 TRCY PMP    230.00   2     -231.4      25.7
    37012 LAKE        230.00   37548 FOLSOM      230.00*  1      -39.4      -2.7
    37013 ORANGEVL    230.00   37548 FOLSOM      230.00*  1     -145.0      16.4
    37021 NATOMAS     230.00   37520 OBANION     230.00*  2     -238.0      34.4
   TOTAL FROM ZONE  322 TO ZONE  325                            -1425.4    226.2

 TOTAL FROM ZONE  322                                           -1859.9    346.3
```

There are 22 on-line machines in the SMUD area, as shown in Table 2-3. The dispatch shown is that represented in the 2017 summer peak load WECC case.

Table 2-3. Base Case Dispatch of SMUD Generation

BUS#	X--NAME -X	BASKV	ID	PGEN MW	QGEN MVAR	MBASE MVA
37301	CAMINO 1	13.800	1	50.0	12.0	75.0
37302	CAMINO 2	13.800	1	50.0	15.0	75.0
37303	CAMPBEL1	13.800	1	50.0	39.0	125.0
37304	CAMPBEL2	13.800	1	50.0	20.0	65.0
37305	JAYBIRD1	13.800	1	60.0	-17.1	77.0
37306	JAYBIRD2	13.800	1	60.0	-17.1	77.0
37309	MCCLELLN	13.800	1	60.0	-4.9	82.4
37310	PROCTER1	13.800	1	40.0	15.0	55.4
37311	PROCTER2	13.800	1	30.0	15.0	55.4
37312	PROCTER3	13.800	1	40.0	15.0	55.4
37313	PROCTER4	13.800	1	40.0	20.0	71.2
37314	ROBBS PK	13.800	1	20.0	6.9	29.7
37315	SRWTPA	13.800	1	40.0	4.3	60.0
37315	SRWTPA	13.800	2	10.0	1.1	20.6
37316	SRWTPB	13.800	1	40.0	4.1	60.0
37317	UNIONVLY	13.800	1	40.0	7.6	46.7
37318	WHITERK1	13.800	1	80.0	17.1	140.0
37319	WHITERK2	13.800	1	40.0	15.2	140.0
37320	UCDMC	12.500	1	25.0	-3.7	27.0
37321	COSUMNE1	18.000	1	120.0	4.8	234.0
37322	COSUMNE2	18.000	1	120.0	4.8	234.0
37323	COSUMNE3	16.500	1	170.0	8.6	228.0

The bus names above are those used in the power flow cases. The names are abbreviated in the power flow case and represent the hydroelectric plants at Camino, Jaybird, Robbs Peak, Union Valley, and White Rock, and the gas-fired Campbell, McClellan, Procter & Gamble, and Cosumnes power plants.

2.1 Dynamic Response of the WI and SMUD Systems Using the Full WI Model

Simulations were performed using the full WECC 2017 summer peak load flow case and corresponding stability data to characterize the dynamic response of the SMUD system to events resulting in a change in frequency. Figure 2-1 shows the response of system frequency and total tie-line power to the drop of 120 MW of generation in SMUD. In this figure, the tie lines are summed in two groups of six lines each; thus, the total import is the sum of the two flows shown with a negative sign indicating flow into SMUD. The system frequency reduction, as expected, is quite small, reaching a minimum of about 0.005 Hz and settling at 0.003 Hz in the post-disturbance steady state. The total frequency bias for the WECC system may be estimated to be approximately 120/0.003/10 = 4000 MW/(0.1 Hz). Note that this estimate represents the frequency bias of this WECC model and may not necessarily be representative of the actual bias or the bias settings used by WECC for actual AGC controls, which are determined by the measured response of the system to actual events.

The total active power flow from the outside world (the WI) to SMUD was increased by 116.3MW, which differs from the lost 120 MW of generation by 3.7 MW. In other words, SMUD generation initially picks up about 3.7 MW of the lost generation. The frequency bias for the SMUD system can thus be estimated to be approximately 3.7/0.003/10 = 123 MW/(0.1 Hz).

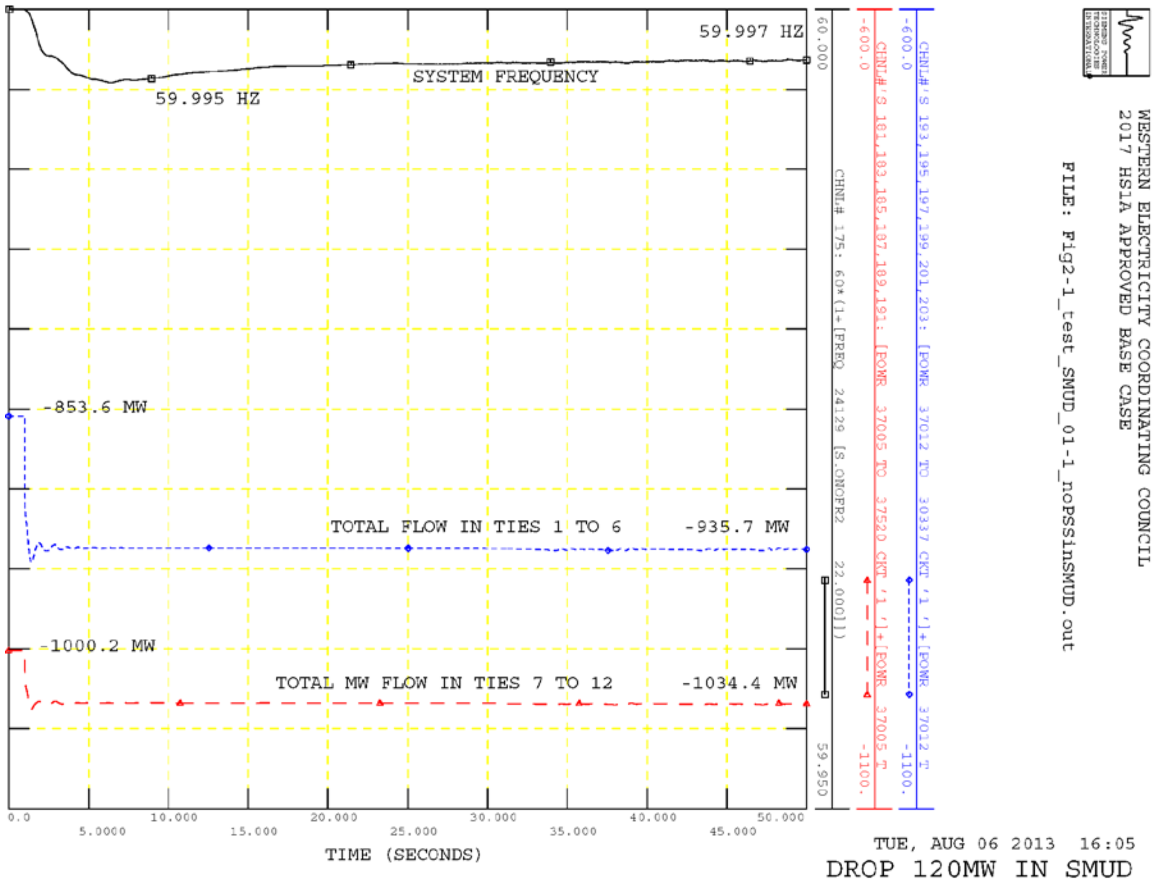


Figure 2-1. System Frequency and Intertie Flow in Response to a Drop of 120 MW of Generation in SMUD as a Part of the Overall WI System

2.2 Equivalent Model of the SMUD System

For studying the response of secondary frequency control, an equivalent of SMUD and the outside WI system was built as follows:

1. The entire SMUD system was retained with boundary 230 kV buses as shown in Table 2-2.
2. The outside WI system was replaced by a single machine and load equivalent connected to the 230 kV bus number 30000.
3. The size of the equivalent machine was assumed to be 250,000 MVA. This machine was dispatched at 190,000 MW, which is about the same as the total WI generation in the original case.
4. The load of 188,150 MW results in a power flow of 1,850 MW delivered to SMUD, again selected to be similar to the tie flow in the original case.
5. All 12 tie lines from the original case were retained but their remote ends (line terminals remote from the SMUD system) were rerouted onto the single WI equivalent bus number 30000.

The one-line diagram of the SMUD system boundary buses and the single machine and load equivalent of the WI is shown in Figure 2-2.

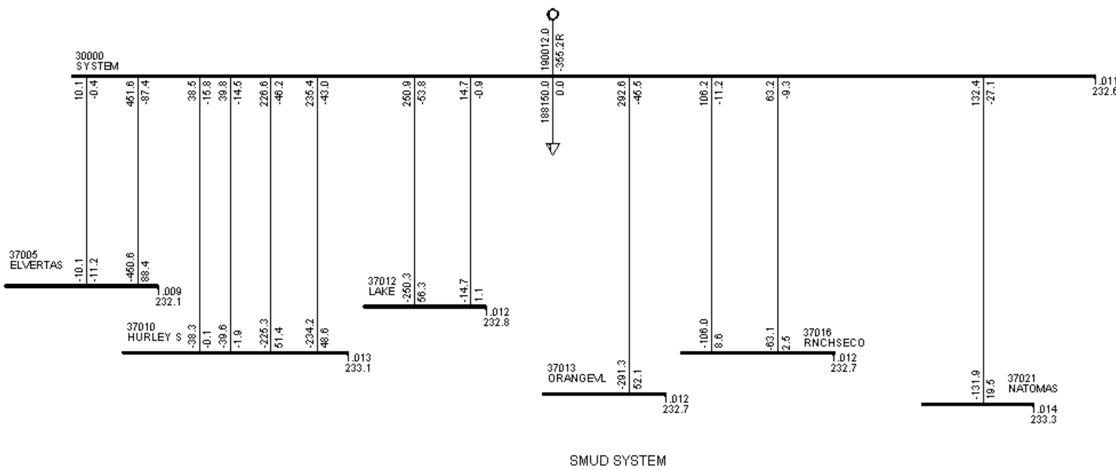


Figure 2-2. SMUD Boundary Buses and WI Single Machine and Load Equivalent for AGC Studies

The unit representing the WI was simulated in dynamics as a thermal unit with a generator, excitation system and turbine governor model. The data for this equivalent unit is shown in Appendix B, Figure B-1.

The same transient as simulated above using the original system (full WI model), that is, the drop of 120 MW of generation, was simulated using this equivalent system. The response of system frequency and total active tie-line power flow of the 12 tie lines (again shown as two groups of six lines) are shown in Figure 2-3. The equivalent system demonstrates a response quite similar to the original case and is thus shown to be adequate to demonstrate the characteristics of secondary frequency control as related to the application of advanced PSH units in the SMUD area.

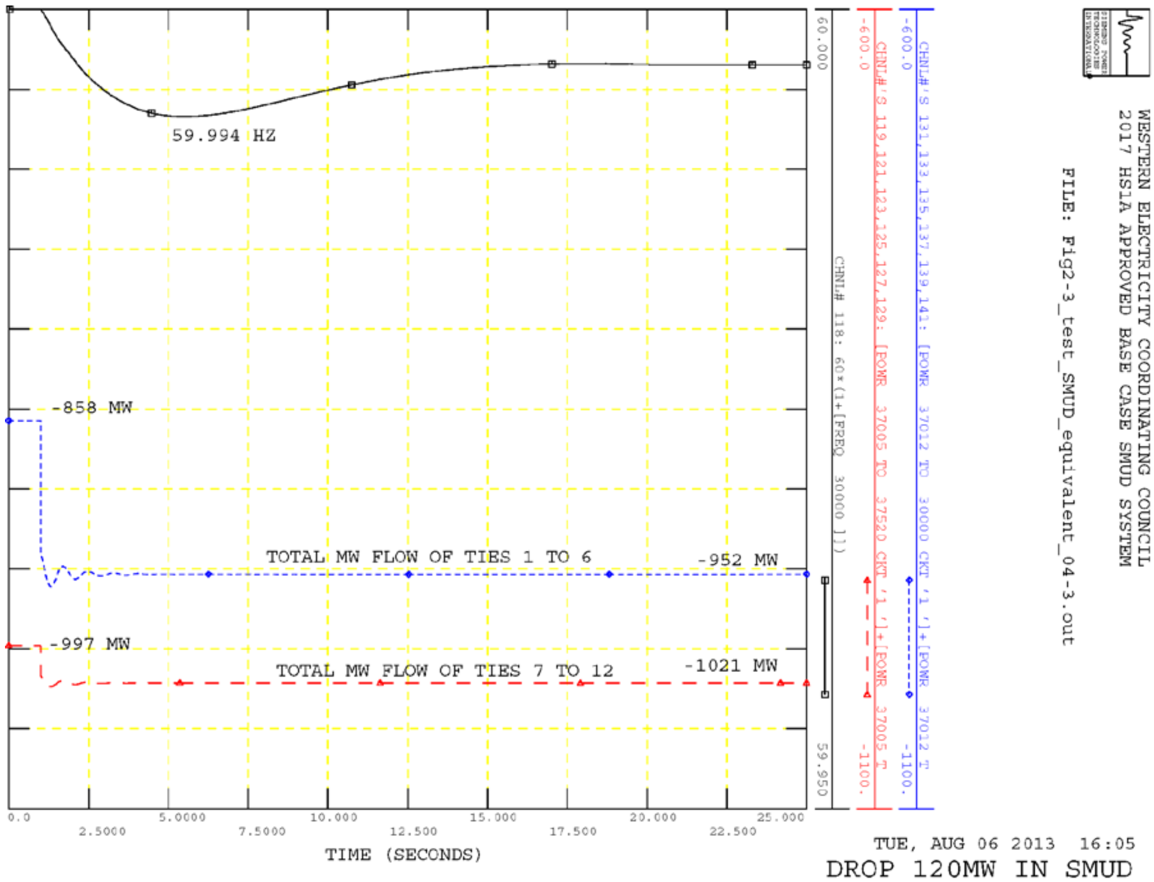


Figure 2-3. System Frequency and Intertie Flow in Response to a Drop of 120 MW of Generation in the SMUD Equivalent

Figure 2-4 depicts a simulation of an event resulting in the ramping down of a significant part of the SMUD generation. It may be construed as representing, for example, a drop in the power available from renewable generation due to a change in wind speed or solar irradiance. From the original 1,235 MW of total SMUD generation, the total generation is ramped down by 285 MW over 1.93 seconds, which corresponds to a ramp rate of about 150 MW/sec. Because this generation change as compared to the size of the WI is very small, the frequency change is negligible, as expected. Power flows in the tie lines from SMUD to the WI increase following the generation reduction as most of the power is initially supplied by the entire WI, which is much larger than the SMUD component. As only primary frequency control is modeled, the frequency settles at slightly below nominal and the tie flows remain at their post-disturbance values.

The following sections will demonstrate how the addition of the AGC model results in the restoration of both frequency and total tie-line power flow to the original values.

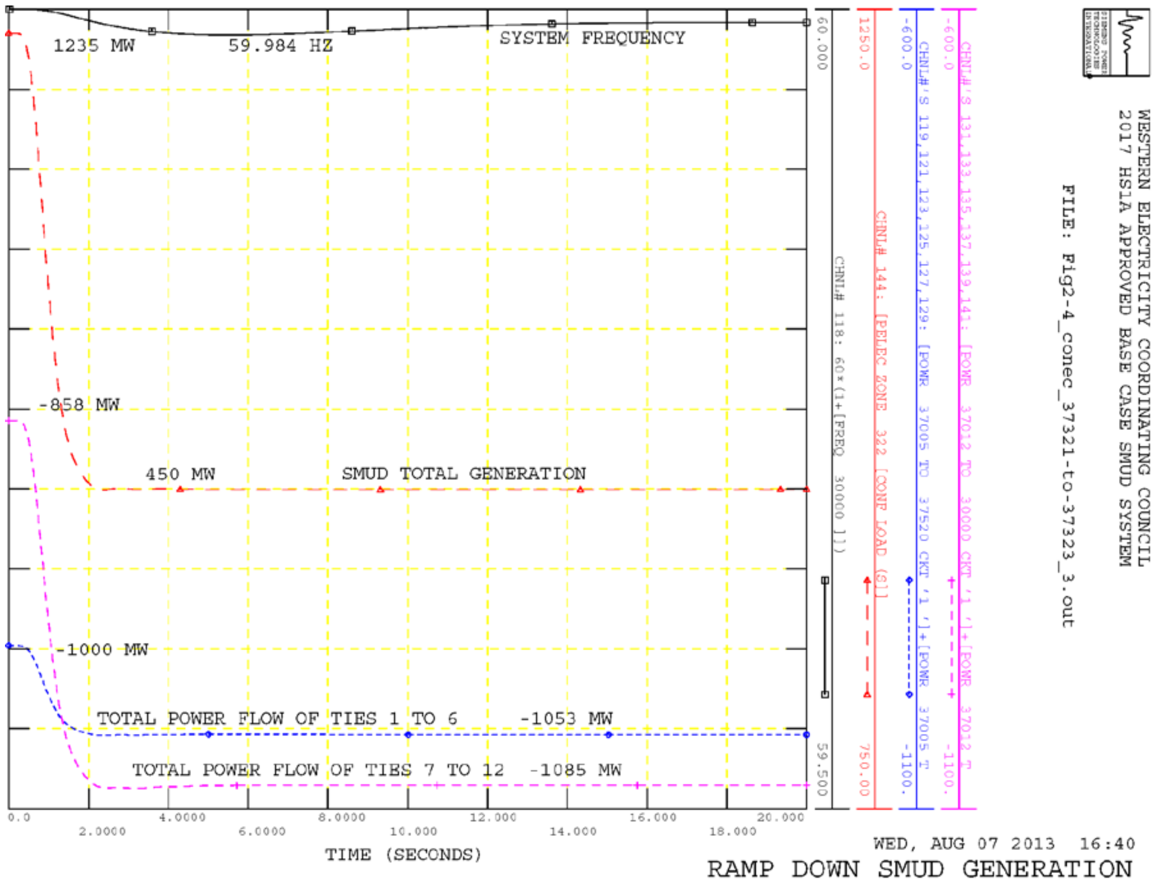


Figure 2-4. System Frequency and Intertie Flow in Response to a Ramp Down of 285 MW of Renewable Power in SMUD

Section

3

Description of the AGC Model

A mismatch between load and generation in interconnected systems results in deviations of tie flows and frequency. The response of the power controls to restore these quantities to their pre-disturbance values is split between primary frequency control and secondary frequency control. Primary frequency control is performed by the turbine governors. Primary frequency control adjusts generation to limit frequency deviation but does not restore frequency or tie flows to their pre-disturbance values. Restoring frequency back to its nominal value (60 Hz in the United States) and tie flows to their pre-disturbance values is the role of secondary frequency control (also often referred to as automatic generation control [AGC]). This section describes the modeling of these AGC controls.

3.1 Supplementary Control — Isolated Power Systems

In an isolated power system, a mismatch between prime-mover power and connected load results in a frequency deviation of sufficient magnitude as required to bring a balance between mechanical and electrical powers. Frequency deviation is therefore a direct indicator of this mismatch between generation and connected load. Restoration of frequency deviation to zero through supplementary control accomplishes the objective of matching generation to load.

Reset action or integral action in the supplementary control ensures zero frequency error in the steady state. The gain of the integral action in the supplementary control is limited by control stability considerations. Figure 3-1 illustrates a typical isolated area frequency performance with and without supplementary control following a step load change. A step in the load is simulated at time equal 1 second (shown as ΔL). Frequency or machine speed (shown as $p\delta$) drops due to the generation/load imbalance. The governors on the generators see this change in their speeds and respond by increasing their mechanical powers. Note that the response is initially the same with or without supplementary control, as the initial response is due only to primary controls (i.e., the governor response). Without secondary control, the frequency settles at a steady state error determined by the change in load, governor droop, and system load frequency dependence. With supplementary control, the frequency is restored to its initial nominal value. Note that in this case, the secondary control is quite responsive, but may need to be slower for some systems to ensure stable and well-damped control.

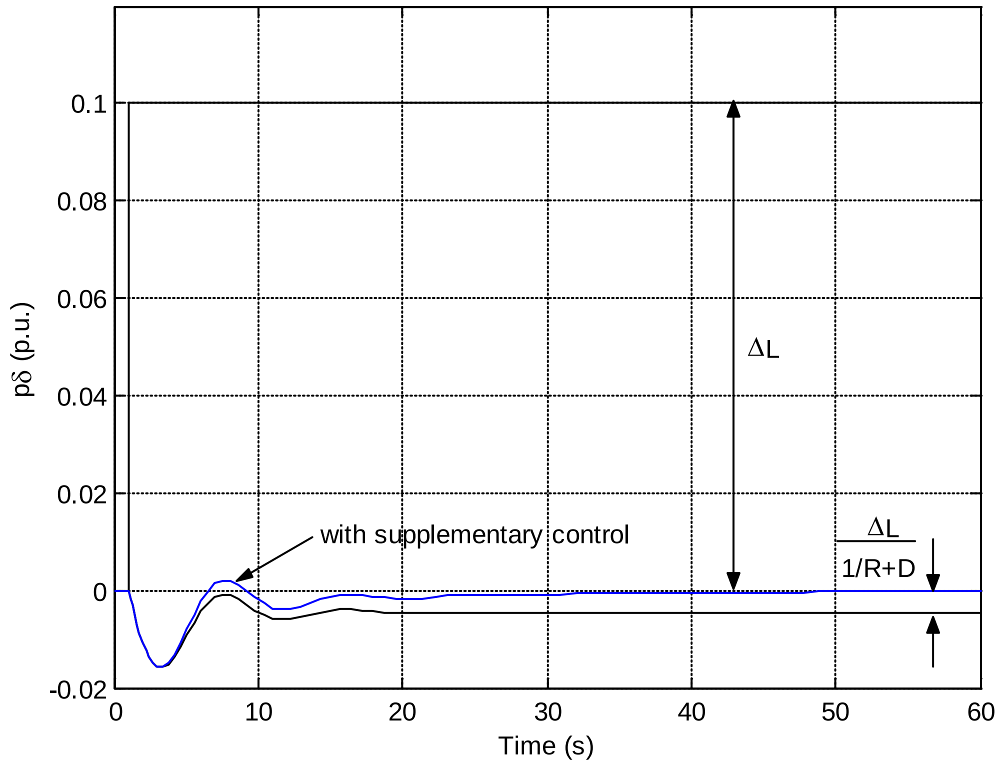


Figure 3-1. Frequency Control in Isolated System with and without Supplementary Control

3.2 Supplementary Control - Interconnected Power System

A mismatch between load and generation in interconnected systems results in deviations of tie flows and frequency. In the usual case of areas interconnected to others that are part of a very large power pool, frequency deviations are very small, and the basic effect of a load change in an area is felt as a deviation in the tie flow between the area and neighboring systems.

Keeping in mind that a basic objective of supplementary control is the restoration of balance between area load changes and area generation changes, this basic objective is met when control action restores frequency deviation to zero and tie-line deviation to zero. This leads to the concept of the area control error (ACE) made up from tie-line deviation added to frequency deviation weighted by a bias factor.

This concept, also known as “tie-line bias load frequency control”, is based on the following objectives:

Supplementary control in a given area should correct for load changes in that area but should not be acting to supply load changes in the other area beyond the contribution made by virtue of frequency deviation through its area regulating characteristic.

In effect, it is desired that if the load change is in area 1, there should be no supplementary control action in area 2, but only action in area 1.

In a two-area system, a load change in area 1 results in tie-line deviation and a frequency deviation. From the point of view of the other area, area 2, this load change in area 1 results in a tie-line deviation equal but opposite in sense to the tie-line deviation experienced by area 1. Of course, area 2 also feels the same frequency deviation.

It can be seen that using a weighting factor of (1/R2 +D2), where R is the governor regulation and D is the load damping factor, on frequency deviation for area 2 (known as the bias factor), a supplementary control signal, ACE, can be formed by adding tie-line deviations to this bias factor times the frequency deviation.

Thus, for area 2, this ACE would be $\Delta P_{TL21} + B_2 p\delta$, which, with B2 = (1/R2 +D2), would yield ACE = 0 for the case in question of load change in area 1.

For area 1, however, the ACE would be $\Delta P_{TL12} + B_1 p\delta$, which, with B1 + (1/R1 +D1), would yield ACE = ∆L.

Therefore the composite error signal made up of tie-line deviation plus a bias factor equal to the area's regulating characteristic (1/R + D) has the right intelligence as to which area should exert supplementary control effort.

Although this concept is based on steady-state relations of system performance under governing duty, a number of dynamic studies and operating experience have confirmed that the use of a bias factor close to the area's steady-state regulating characteristic gives close to optimal control from the standpoint of dynamic non-interaction between areas.

Figure 3-2 shows the block diagram of two areas with supplementary control.

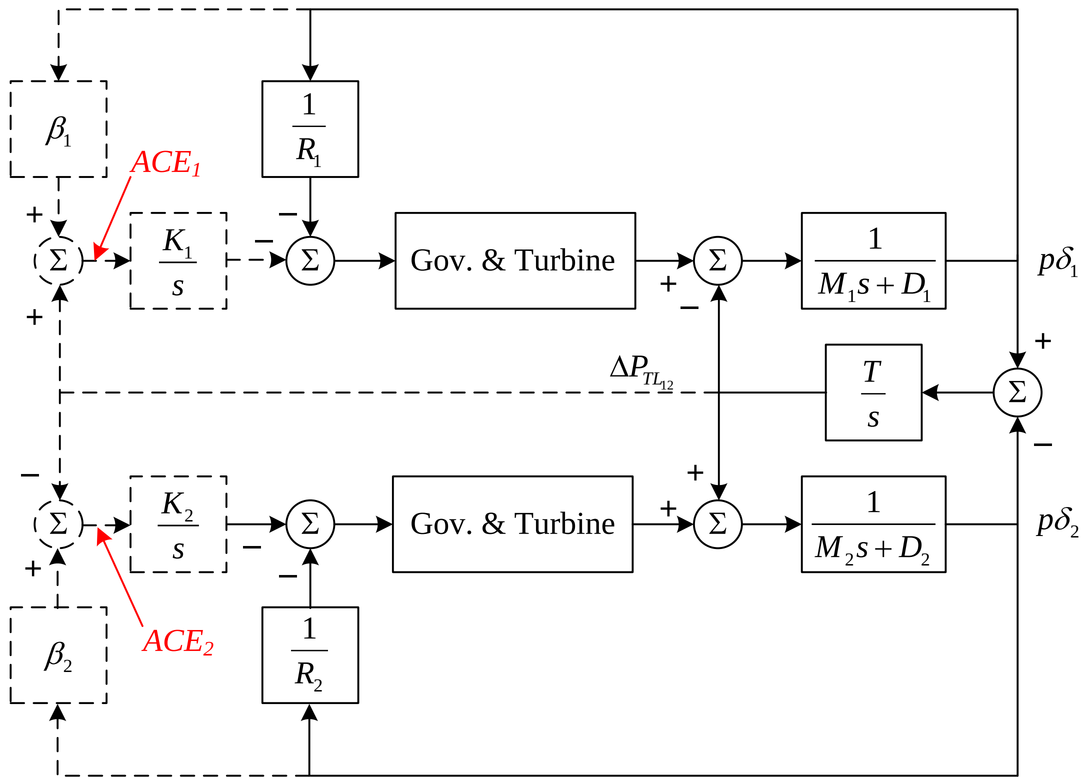


Figure 3-2. Block Diagram of Two-Area System with Supplementary Control

It should be noted that steady-state considerations show that it is not critical to have the bias factors set exactly equal to the regulating characteristic. As a matter of fact, in order to reach the final result of $\Delta P_{TL} = 0$ and $p\delta = 0$, almost any combination of area control errors that contain components of frequency and tie-line deviation will ensure the ultimate restoration of tie-line deviation and frequency deviation to zero. This is apparent from the fact that integral action ensures the reduction of area control error to zero in the steady state.

$$ACE_1 = k_1 \Delta P_{TL12} + \beta_1 p\delta = 0$$

$$ACE_2 = k_2 \Delta P_{TL21} + \beta_2 p\delta = 0$$

Thus, for non-zero values of k_1, k_2, β_1, and β_2, the above equations will yield $\Delta P_{TL} = 0 \; and \; p\delta = 0$ independent of the values of k_1, k_2, β_1, and β_2.

A mode of control which will also satisfy the objectives of $\Delta P_{TL} = 0$, $p\delta = 0$, is to assign one area to control tie-line deviations (called flat tie-line control) and the other area to control frequency (called flat frequency control). In general, this mode of control results in poorer dynamic performance than the mixed mode with tie-line bias.

In addition to the task of controlling frequency and holding net interchange schedules, a very important secondary function is the distribution of the desired generation among the many sources so as to minimize operating costs. This is performed by allocating generation to achieve equal incremental costs.

There are many ways to implement an AGC system. In the most basic sense, a signal proportional to area control error (ACE) is transmitted to the various units' speed changers, or load reference motors. The speed changer positions or load reference values change at rates proportional to the transmitted signal, which is generally in the form of pulses. An alternate implementation is the transmitting of set points to be delivered to a plant computer control system for implementation.

The AGC system must allocate the required ACE among the available units to ensure an appropriately fast system response while sharing the required change and not inducing undue stresses on individual units.

The advent of the modern digital process control computer and great improvements in data transmission and communication equipment have led to the almost universal practice of developing the control logic, including the process of economic resource allocation, from a central location, that is, the dispatch center. In addition to the area control error, unit MW loadings are telemetered to this central location where economic allocation equipment develops the desired generation for each unit.

The basic computation of unit control error is performed every T seconds by the load frequency control program, with a typical cycle time of around 4 seconds. The updating of economic loading parameters (base points and participation settings) is performed much less frequently by an auxiliary program called an economic dispatch program.

With the use of digital computers there are a number of sophisticated control logic schemes that may be executed. The use of regulating forcing action, sometimes labeled "assist action," is common. The idea here is that, depending on the size of the area control error, it may be desirable to move all units irrespective of the dictates of economic loading. This scheme adds a "regulating" component from ACE with or without deadband to the unit control errors. When ACE is reduced to zero, the various units would automatically be reset to their economic loading point.

Of course, there are many implementation details. For example, filtering is employed so the AGC system does not react to random noise, that is, the AGC calculation rejects unnecessary and ineffective control action without inhibiting the ability of units to maintain economic loading. More advanced capabilities — such as the capability to ramp units to account for daily load cycles by predictive actions, time error correction, unit tracking logic, etc., — are beyond the scope of this study but are very important in the actual implementation. However these capabilities are generally not important in the timeframe of the analysis of long-term dynamics that is focused on the response to system disturbances.

3.3 The AGC Model

This section describes the model developed to represent the Automatic Generation Control (AGC). This model was developed as a PSS®E user-written model and is compatible with the latest PSS®E revision.

The AGC model is named AGC01. Its block diagrams are shown in Figure 3-3 through Figure 3-8. The model data sheet is provided in Appendix A.

3.3.1 AGC Algorithm

Each generating unit that is allowed to participate in AGC has one of three control modes:

1. Base control mode
2. Base and Regulating control mode
3. Automatic control mode

Generators that will never be modeled as participating in AGC do not have to be entered into the AGC model data.

Units in Base control mode do not participate in AGC. However, the data associated with these units (participation factors, limits, etc.) are stored in the model. This approach provides the ability to model a unit that can at times participate in the AGC but is not participating in the event being presently simulated.

Units in Base and Regulating control mode participate in AGC and contribute to regulation through a normal regulation contribution and, if required, an emergency assistance contribution. These contributions are defined below.

Units in Automatic control mode also participate in AGC and contribute to regulation through a normal regulation contribution and, if required, an emergency assistance contribution. The units in Automatic control mode also have an economic regulation contribution (defined below). Units in this control mode are controlled by AGC to operate at any generation level within the defined limits so as to provide instantaneous system regulation and to economically satisfy system load requirements. The economic base points and economic participation factors would be calculated by the Economic Dispatch function. This calculation is performed periodically by the AGC system, but for the PSS®E model and time frame, the units are assumed to be at their base points in the initial steady state, that is, the load flow case, and the participation factors for each unit are defined by model constants.

ACE is calculated as frequency multiplied by 10βf added to the deviation in tie flow from scheduled tie flow, as shown in Figure 3-3. Note the sign convention is such that the frequency bias βf is a positive number and has units of MW per 0.1 Hz. Tie flow is defined with the sign convention such that area export is positive and the units are MW. Both measured frequency and tie flow are filtered using a single lag filter, with the ability to select different filter time constants for each signal.

$$\text{ACE} = \Delta f(10\beta f) + (\text{TIEact} - \text{TIE set})$$

AGC operation is disabled if frequency deviation exceeds F_{lim} in either the positive or negative direction, where F_{lim} is given in Hz. There is also a switch, ICON(M), to turn the AGC model on or off.

The ACE signal can also be filtered. As the signals are defined, ACE is negative for the condition where generation must be increased. There is the capability to add a gain, KACE, to boost ACE if so desired. The output ACE signal following the gain KACE is GFACEN.

The formation of the Unit Control Error (UCE) is shown in Figure 3-4. For units in Base and Regulating mode, the desired generation POD_N is calculated for Unit N as:

$POD_N = PBASE_N + NR_N + EA_N$

Where:

- POD_N is the unit's desired generation, MW
- $BASE_N$ is the unit's base point, MW
- NR_N is the unit's normal regulation contribution, MW
- EA_N is the unit's emergency assist contribution (if required), MW

For units in the AUTOMATIC control mode, the desired generation, POD_N is calculated for Unit N as:

$POD_N = BASE_N + ER_N + NR_N + EA_N$

Where:

- $BASE_N$ is the unit's base point, MW
- ER_N is the unit's economic regulation contribution, MW
- NR_N is the unit's normal regulation contribution, MW
- EA_N is the unit's emergency assist contribution (if required), MW

The unit control error (UCE) is calculated as the difference between the desired and actual generation and has the units of MW:

$UCE_N = POD_N – PactN$.

Actual generation is passed through a first-order lag filter.

The normal AGC regulation action is handled by the controls shown in Figure 3-5. NRN is the regulation contribution for unit N in MW and is calculated for units in the Base and Regulating and Automatic control modes.

$$NR_N = \frac{RF_N}{\sum_N RF_N} GFACE_N$$

Where:

- NR_N is the normal regulation contribution for unit N, MW
- $GFACE_N = -K_{ACE} * FACE$, MW
- RF_N is the normal regulating factor for the unit
- $\sum_N RF_N$ is the sum of the RFs for all units in the Base and Regulating and Automatic

control modes

If the magnitude of FACE exceeds K1 (where both have units of MW), an additional emergency assist contribution can be supplied and is calculated as follows and shown in Figure 3-6.

$$EA_N = \frac{AF_N}{\sum_N AF_N}(K1 - FACE) \quad if \quad FACE > 0$$

$$EA_N = \frac{AF_N}{\sum_N AF_N}(-K1 - FACE) \quad if \quad FACE < 0$$

Where

- EA_N is the emergency assist contribution for unit N, MW
- K1 is the emergency assist action threshold, MW
- AF_N is the emergency assist factor
- $\sum_N AF_N$ is the sum of the AFs for all units in the Base and Regulating and Automatic control modes

Note that when a unit is at its limit (Pmax or Pmin) and the sign of FACE is in the direction to keep the unit on that limit, the total regulating factors $\sum_N RF_N$ and $\sum_N AF_N$ are recalculated without that unit's participation factor included in the summation. Thus, the regulating capability that is lost because of this unit being on limit is reallocated to other units that have the capability to respond.

The economic regulation contribution of a unit in the Automatic control mode is calculated as shown in Figure 3-7. Note that this component is only calculated for units in Automatic mode, and not for those units in Base and Regulating mode.

$$ER_N = \frac{EPF_N}{\sum_N EPF_N} SUME$$

Where:

- ER_N is the economic regulation contribution for unit N, MW
- EPF_N is the economic participation factor for unit N
- $\sum_N EPF_N$ is the sum of the EPFs for all units in the Automatic control mode

- SUME is the difference between the total generation of all units in Automatic mode and the sum of their base points, MW

Note that when a unit is at its limit (Pmax or Pmin) and the sign of SUME is in the direction to keep the unit on that limit, the total economic regulating factor $\sum_{N} EPF_N$ is recalculated without that unit's participation factor included in the summation. Thus, the economic regulating capability that is lost because of this unit being on limit is reallocated to other units that have the capability to respond.

There is also the capability to have an economic contribution from FACEN as used in some AGC implementations.

The Normal Regulation Contribution (NR_N) provides the necessary allocation to reduce the ACE. The regulation contribution shifts to the economic contribution as ACE is reduced for the units in the Automatic mode. As soon as ACE is reduced to a satisfactory level, all units in the Base and Regulating control mode will return to their base points, thus forcing units in Automatic control mode to absorb the difference and adjust their generation accordingly.

The formation of the power setpoints for the units is shown in Figure 3-8. Unit Control Error (UCE) can be adjusted by use of a lead-lag function, which can be used to add lead to compensate for the unit characteristics, for example, the lag effect of a hydroelectric unit. The desired generation output error is checked against high and low rate of change limits. The unit error signal is integrated to obtain the desired change in setpoint. This change in setpoint is limited to ensure that the unit setpoint is within the maximum and minimum power range defined in the AGC data (Pmax and Pmin). Thus, the AGC will not move any unit out of its allowed operating range.

Area Control Error

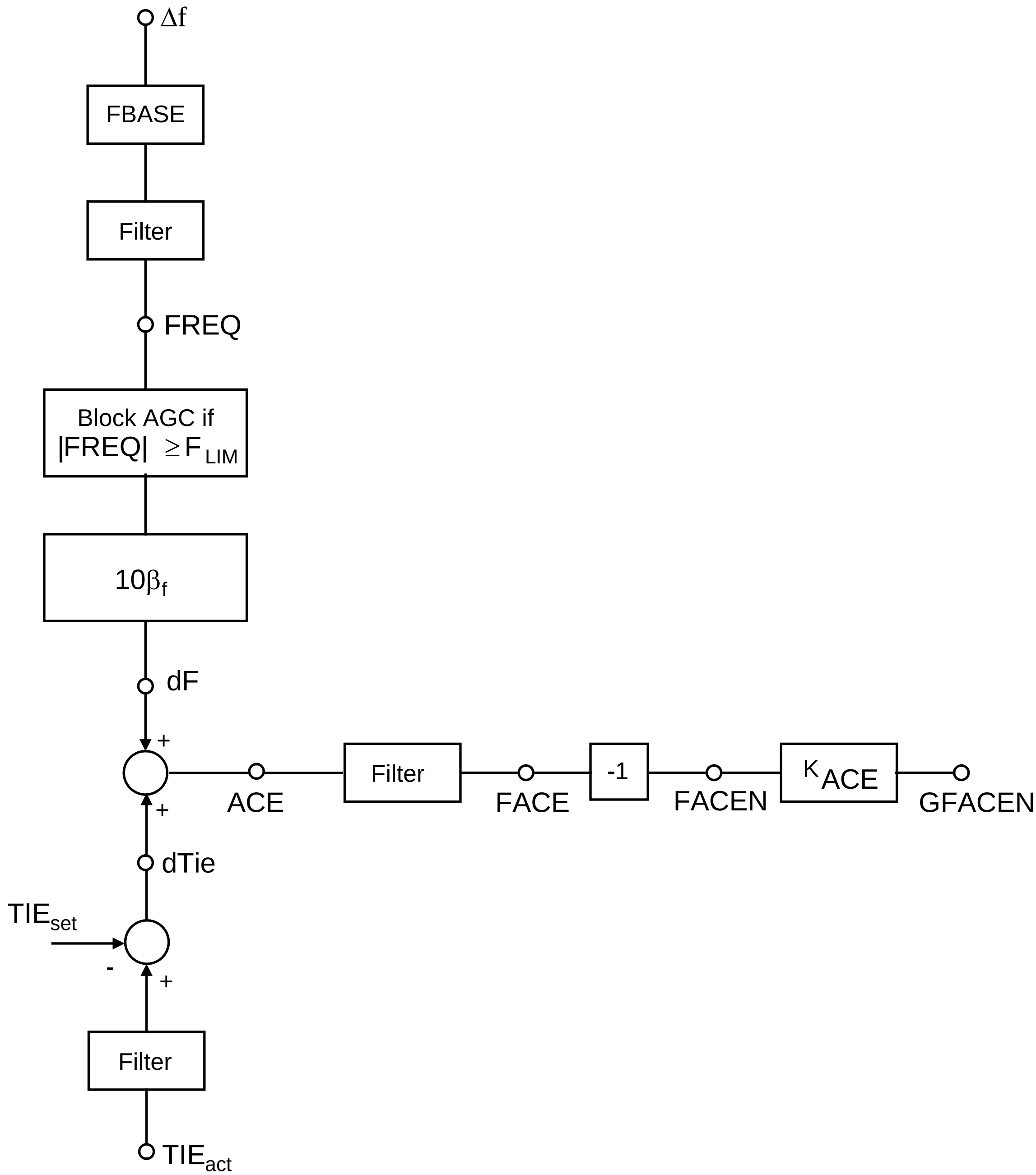
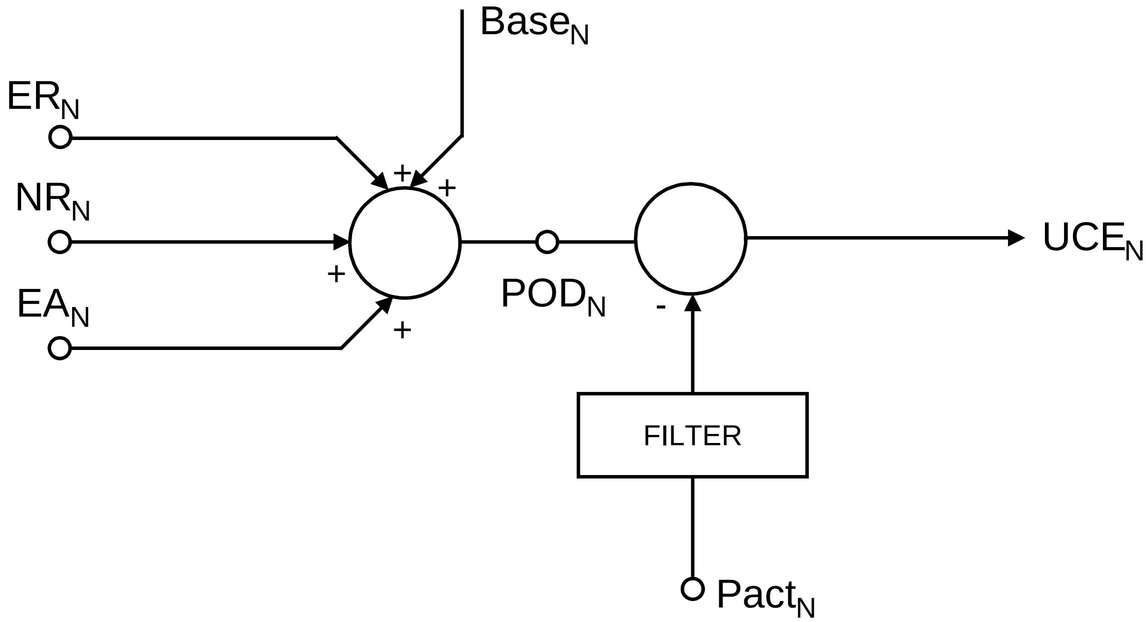


Figure 3-3. Model AGC01 – Area Control Error

Unit N Control Error

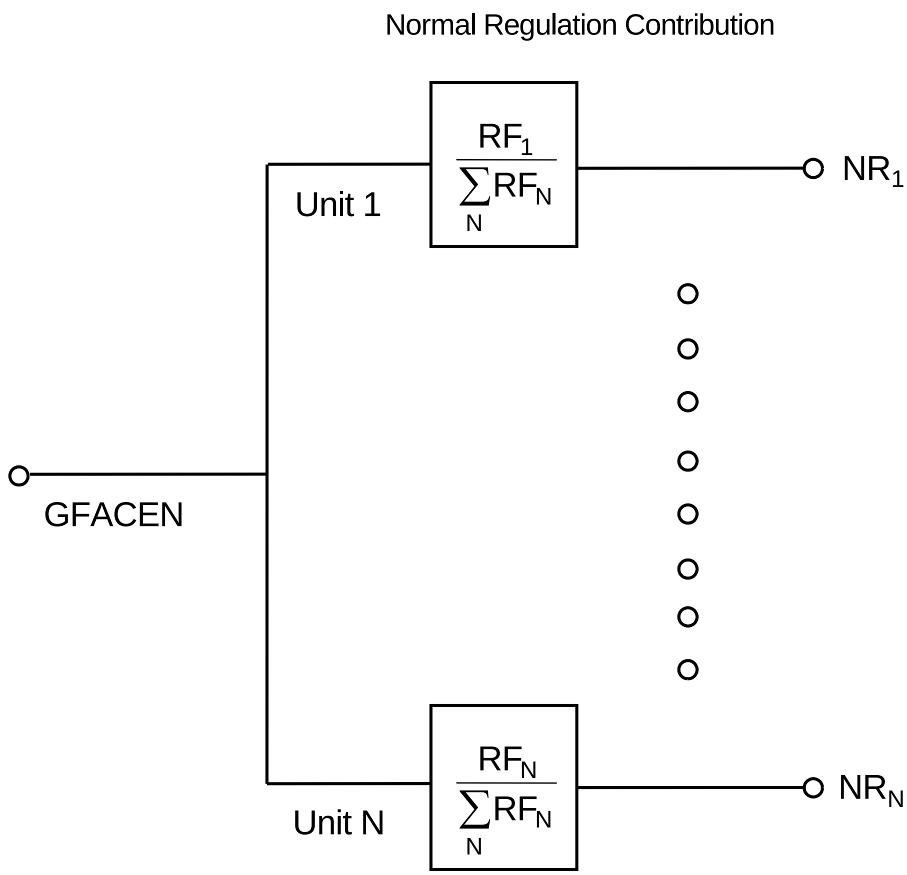


ER$_N$ - Economic Regulation Contribution for Unit N

NR$_N$ - Normal Regulation Contribution for Unit N

EA$_N$ - Emergency Assistance Contribution for Unit N

Figure 3-4. Model AGC01 – Unit Control Error (UCE for Unit N)



$\sum_{N} RF_N$ Summed for all units in Base and Regulating and Automatic Modes

Figure 3-5. Model AGC01 – Normal Regulation Contribution NR for Unit N

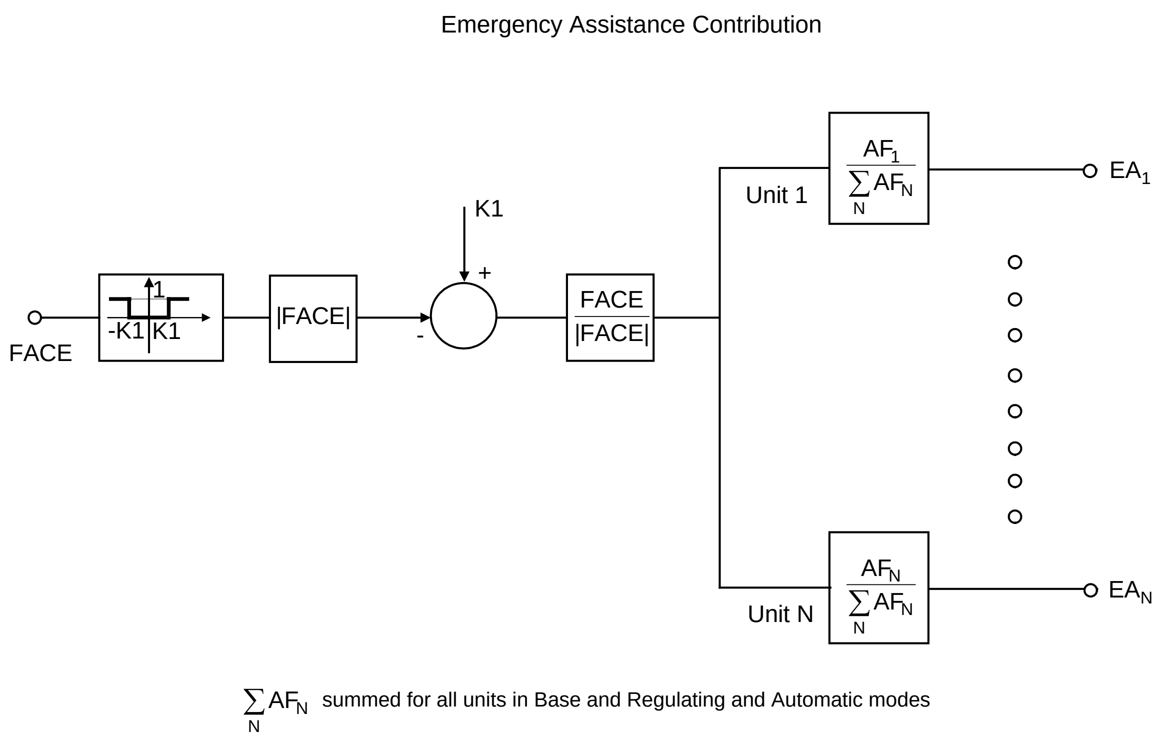
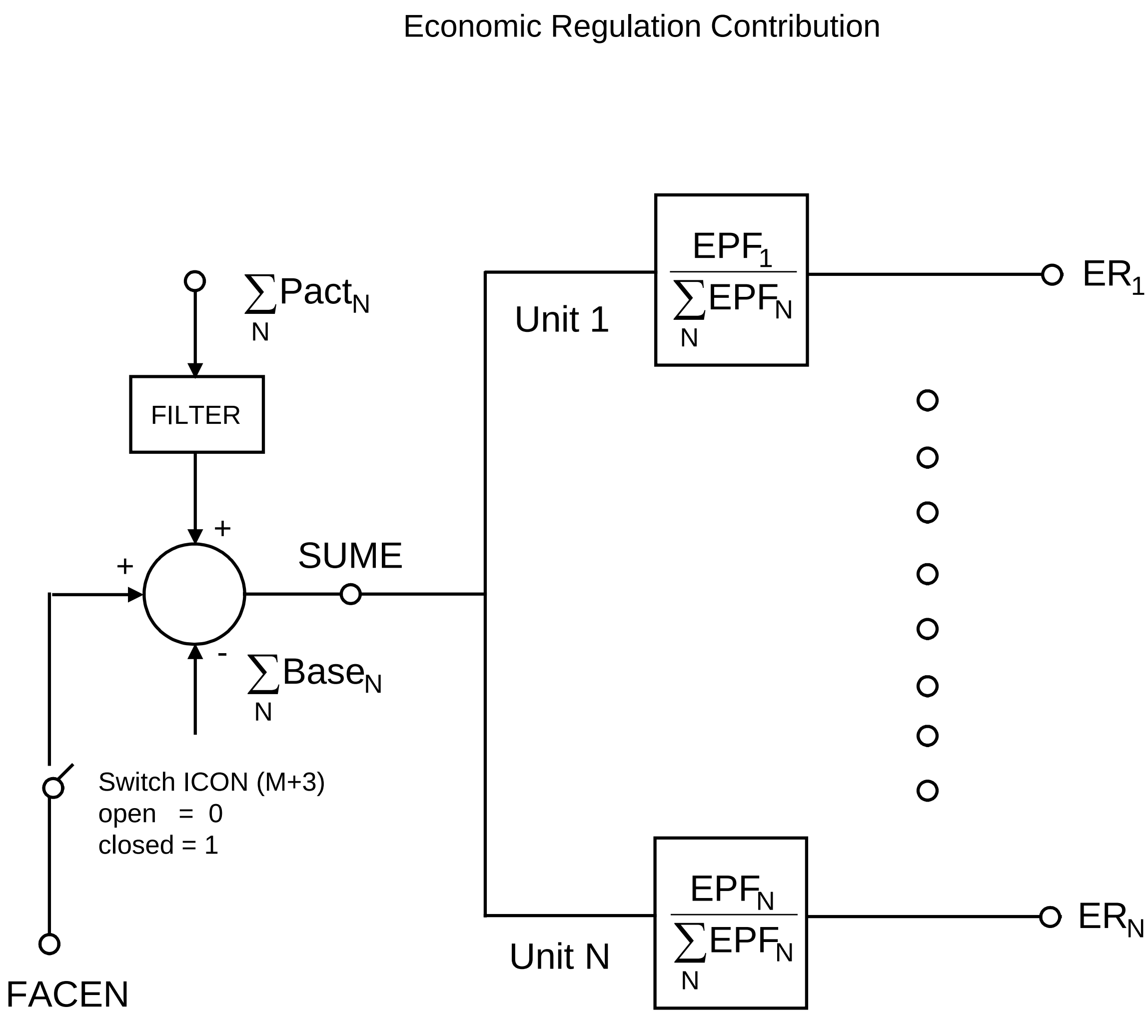


Figure 3-6. Model AGC01 – Emergency Regulation Contribution EA for Unit N



$\sum_N Pact_N, \sum_N Base_N$ and $\sum_N EPF_N$ summed for all units in Automatic Mode.

Figure 3-7. Model AGC01 – Economic Regulation Contribution ER for Unit N

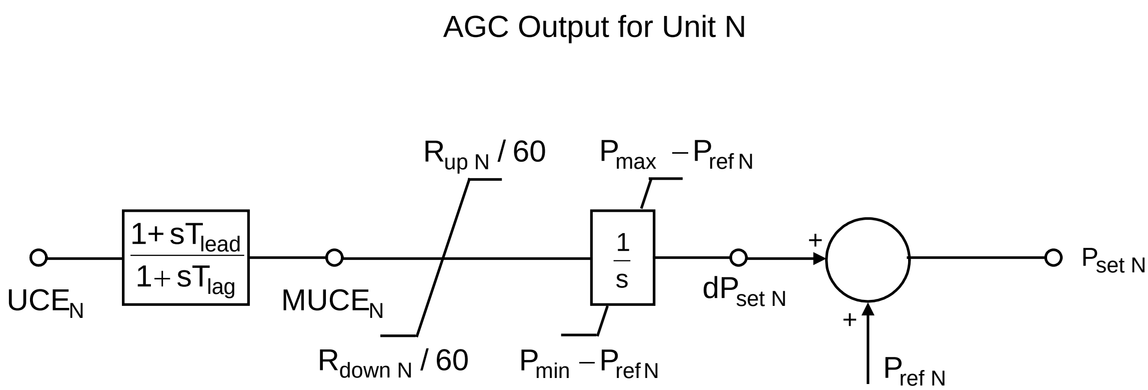


Figure 3-8. Model AGC01 – Calculation of Power Set-Point for Unit N

This page intentionally left blank.

Section

4

Testing the Secondary Frequency Control for the SMUD System

4.1 Modeling the SMUD AGC System

As noted above, the Sacramento Municipal Utility District (SMUD), as a typical balancing authority and a member of the project advisory group, was suggested by the Advanced Technology Modeling TFG as an appropriate example system to be used for testing of the models of the advanced pump storage hydro technology and demonstration of the potential benefits of this technology.

This section describes a model of SMUD's AGC system developed to perform that testing. While effort was made to make the test case representative of SMUD, data on the SMUD AGC system were not available to the testing team. Thus, the model described below is a generic control structure and may not represent the actual AGC implementation employed by SMUD. It was also necessary to assume many model parameters, such as unit ramp rates, which can greatly impact performance. Hence, it is important to note that while the simulations that follow illustrate AGC performance with and without the advanced pump storage hydro technology, any simulations shown here must not be considered to represent actual SMUD performance.

4.2 Conventional Generating Units

All SMUD generating units from the WECC 2017 load flow case are listed in Figure 4-1, along with the associated dynamic simulation models of the generator, excitation system, and turbine-governor.

Bus #	Name	kV	Model	Bus #	Name	kV	Model
37301	CAMINO 1	13.800 1	GENSAE	37313	PROCTER4	13.800 1	GENROU
			ESST1A				AC8B
			IEEEG3				GGOV1
37302	CAMINO 2	13.800 1	GENSAE	37314	ROBBS PK	13.800 1	GENSAE
			ESST1A				ESST1A
			PIDGOV				IEEEG3
37303	CAMPBEL1	13.800 1	GENROU	37315	SRWTPA	13.800 1	GENROU
			ESST1A				EXAC1
			GAST2A				GGOV1
37304	CAMPBEL2	13.800 1	GENROU	37315	SRWTPA	13.800 2	GENROU
			EXAC1				EXAC1
			GAST2A				GGOV1
37305	JAYBIRD1	13.800 1	GENSAE	37316	SRWTPB	13.800 1	GENROU
			ESST1A				EXAC1
			PIDGOV				GGOV1
37306	JAYBIRD2	13.800 1	GENSAE	37317	UNIONVLY	13.800 1	GENSAE
			ESST1A				ESST1A
			PIDGOV				IEEEG3
37307	JONESFRK	4.1600 1	GENSAE	37318	WHITERK1	13.800 1	GENSAE
off-line			ESST1A				ESST1A
			PIDGOV				IEEEG3
37308	LOON LK	13.800 1	GENSAE	37319	WHITERK2	13.800 1	GENSAE
off-line			ESST1A				ESST1A
			WSHYDD				IEEEG3
37309	MCCLELLN	13.800 1	GENROU	37320	UCDMC	12.500 1	GENROU
			EXAC1				EXAC1
			URGS3T				GGOV1
37310	PROCTER1	13.800 1	GENROU	37321	COSUMNE1	18.000 1	GENROU
			EXAC1				ESST4B
			GGOV1				GGOV1
37311	PROCTER2	13.800 1	GENROU	37322	COSUMNE2	18.000 1	GENROU
			EXAC1				ESST4B
			GGOV1				GGOV1
37312	PROCTER3	13.800 1	GENROU	37323	COSUMNE3	16.500 1	GENROU
			EXAC1				REXSYS
			GGOV1				GGOV1

Figure 4-1. All SMUD Generating Units and Associated Equipment Models

All of these units, except for the two off-line units on buses 37307 and 37308, are assumed to participate in AGC. Information identifying these units was included in the AGC model data. This approach allows the AGC model to access the necessary internal arrays and coordinate with the turbine–governor model of each unit, for example, to adjust the reference of the governor model to that determined by the AGC controls.

The parameters of the AGC model with all original units as in Figure 4-1 are included in Appendix B, Figure B-1. Maximum and minimum power and power ramping characteristics were provided by Energy Exemplar and are shown in Figure 4-2.

Generator	Maximum Capacity (MW)	Minimum Stable Level (MW)	Maximum Ramp Up (MW/Min)	Maximum Ramp Down (MW/Min)
Campbells CT1	50	32	5	5
Campbells CT2	50	32	5	5
Campbells ST	62	11.5	10	10
Carson CT1	42	12	10	10
Carson ST	15	6	10	10
Cosumnes CT1	181	84	5	5
Cosumnes CT2	181	84	5	5
Cosumnes ST	177	84	10	10
PG CT1	42	30	5	5
PGCT2	42	30	5	5
PG ST	32	7.5	10	10
Carson Peaker	42	12	10	10
CTX5 2020	100	40	10	10
McClellan	72	50	10	10
PG Peaker	44	20	10	10
UARP	580	30	1.7	1.7

Figure 4-2. Maximum and Minimum Power and Power Ramping Rate for SMUD Units Participating in AGC

The same disturbance that was simulated in Section 2 (Figure 2-3), the drop of 120 MW of SMUD generation, was also simulated with the AGC system modeled. Figure 4-3 shows the system frequency and AGC ACE. Note that the time scale in Figure 4-3 is much longer than that in Figure 2-3 to illustrate the AGC response. Secondary frequency control is significantly slower, by design, than primary frequency control. As the figures show, the initial frequency decay is the same. However, with the AGC controls included in the simulation, frequency is restored back to 60 Hz in about 5 or 6 minutes, as the AGC controls act to reduce ACE back to zero.

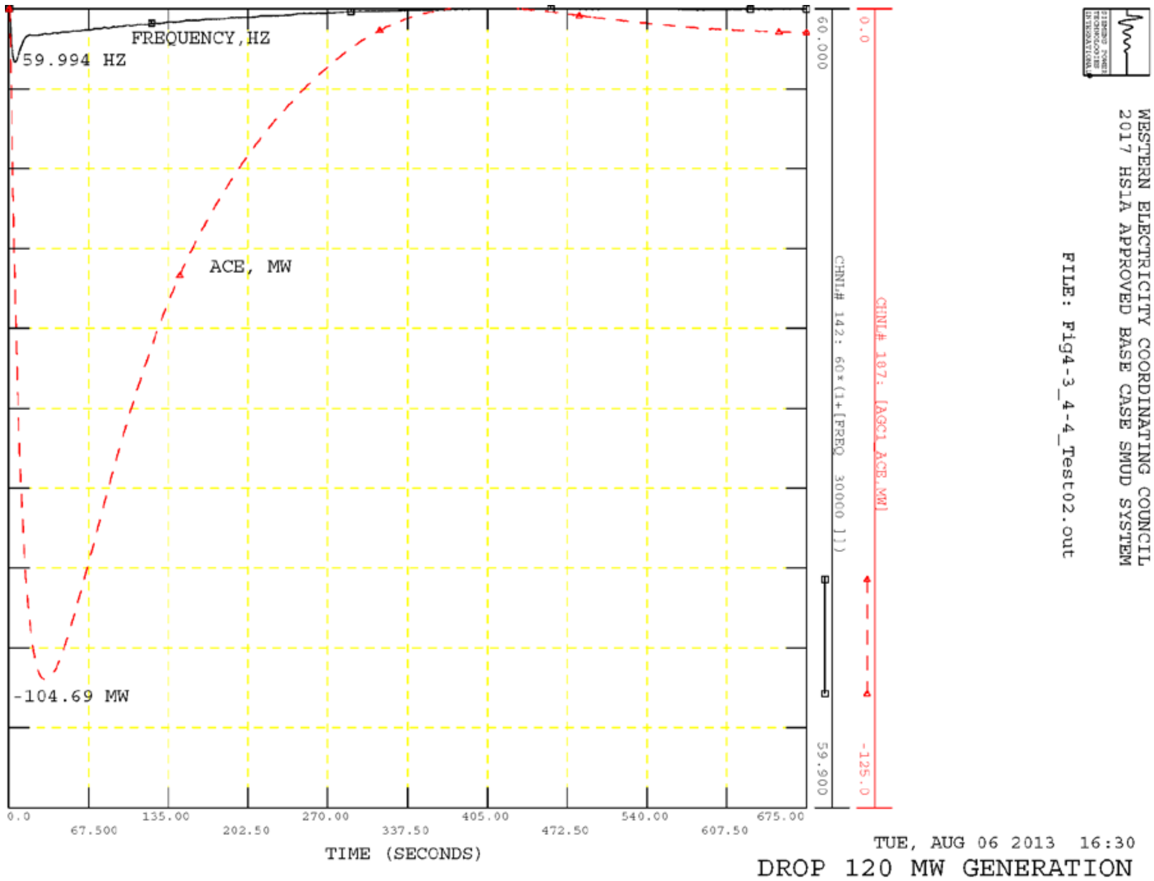


Figure 4-3. System Frequency and AGC ACE in Response to an Underfrequency Event with All Conventional Units

Figure 4-4 shows the total mechanical power of all the SMUD units and the total tie flow into SMUD (the sign convention is defined such that a negative flow represents an import into SMUD). The 120 MW drop in total mechanical power of SMUD units due to the trip of one unit is clearly seen. The AGC action returns both quantities to their initial values. Note that while the total mechanical power of all SMUD units returns to its initial value, the mechanical powers of individual SMUD units have increased to replace the power lost from the tripped SMUD generator.

The next test of the AGC model involved simultaneously dropping 3 generating units in SMUD totaling 410 MW of generation. This event is much more severe than the previous one, both because the loss in generation is about 3.4 times larger but also because there are fewer SMUD machines remaining on-line to respond to and help a recovery from the event. Figure 4-5 shows the system frequency and AGC ACE. Note that neither of these quantities returns to their initial values as a result of AGC action as seen in the previous example. The explanation can be seen from Figure 4-6 where the total SMUD mechanical power is shown. The total mechanical power is not able to increase back to the initial value because SMUD units participating in AGC hit their maximum power limits. This can be seen in the plots of active power of several SMUD units participating in AGC in Figure 4-7, which show units reaching their maximum values.

Note that the rate at which power is increased on a unit is determined by the amount of change required (its contribution to the ACE), the ramp rates in the AGC model data (maximum and minimum controller action), and the ramp rates in the governor model (representing physical capabilities of the prime mover). The amount of power change is determined by the amount of change required to return ACE to zero, the individual unit's regulating factor in relation to the total area regulating factor (the unit's contribution to area regulation), and the maximum limits of the unit (lower of either of the limits in the AGC or governor model).

For this study, the regulating factors (RFs) were set in proportion to the unit MVA size MBASE. Thus, larger units participated proportionately more than smaller units. This is not necessarily the case in the actual system, where response is not proportional to unit size because individual units or plants may have physical or operating limits that restrict their ramping capabilities.

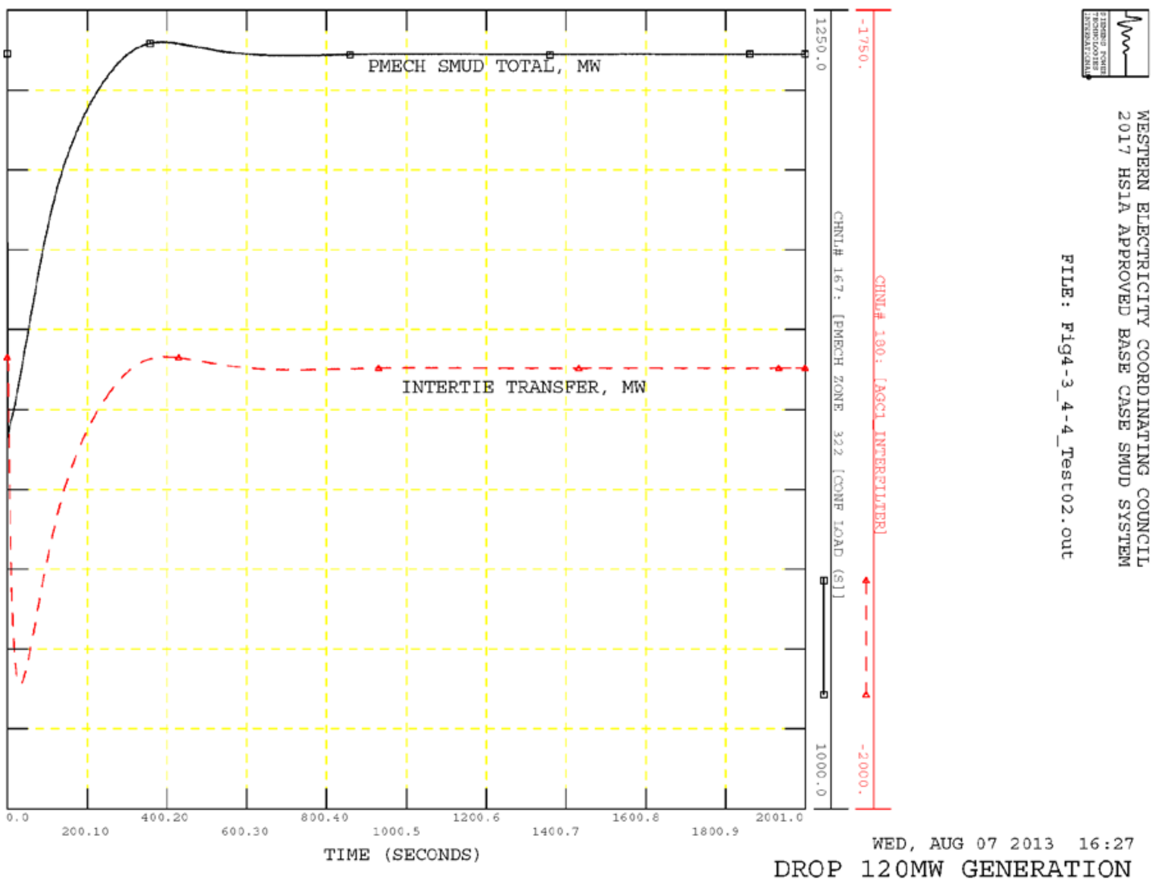


Figure 4-4. Total SMUD Mechanical Power and AGC Intertie Transfer in Response to an Underfrequency Event with All Conventional Units

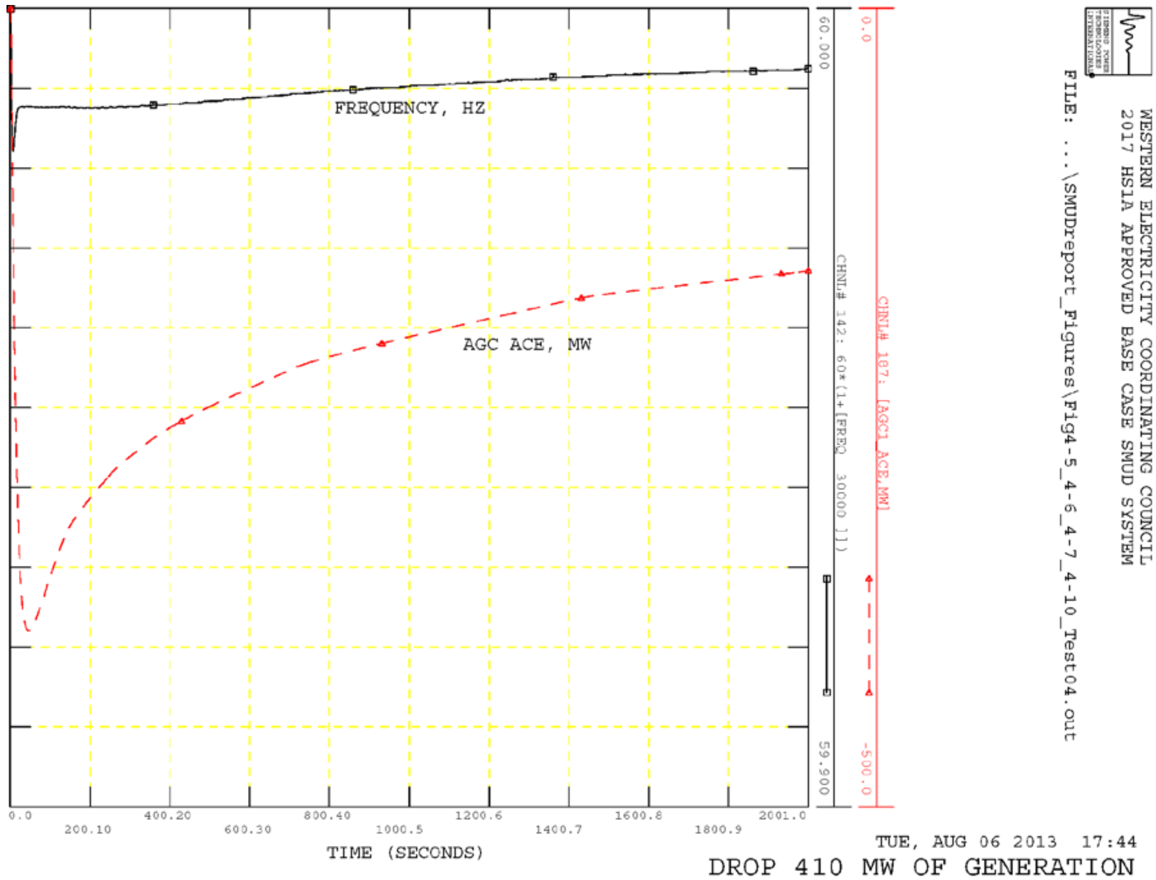


Figure 4-5. System Frequency and AGC ACE in Response to an Underfrequency Event with All Conventional Units

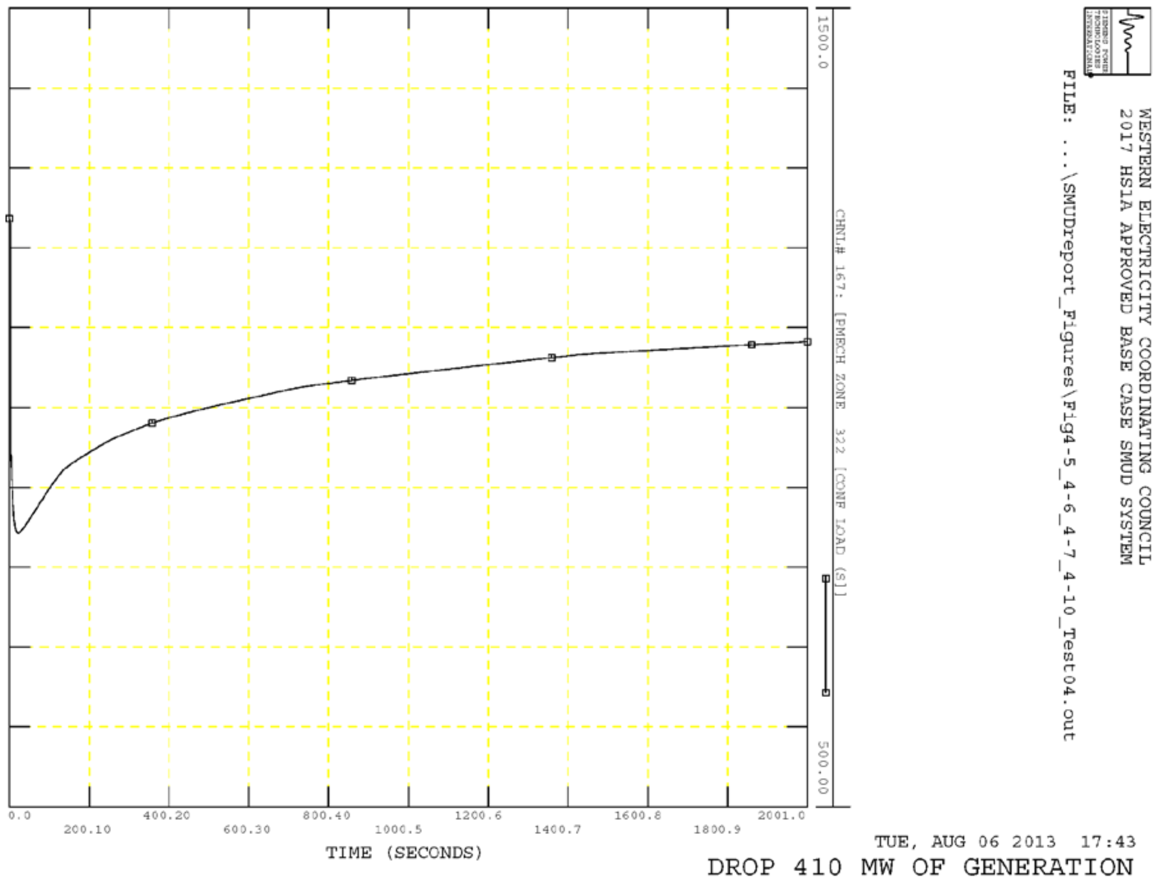


Figure 4-6. Total SMUD Mechanical Power in Response to an Underfrequency Event with All Conventional Units

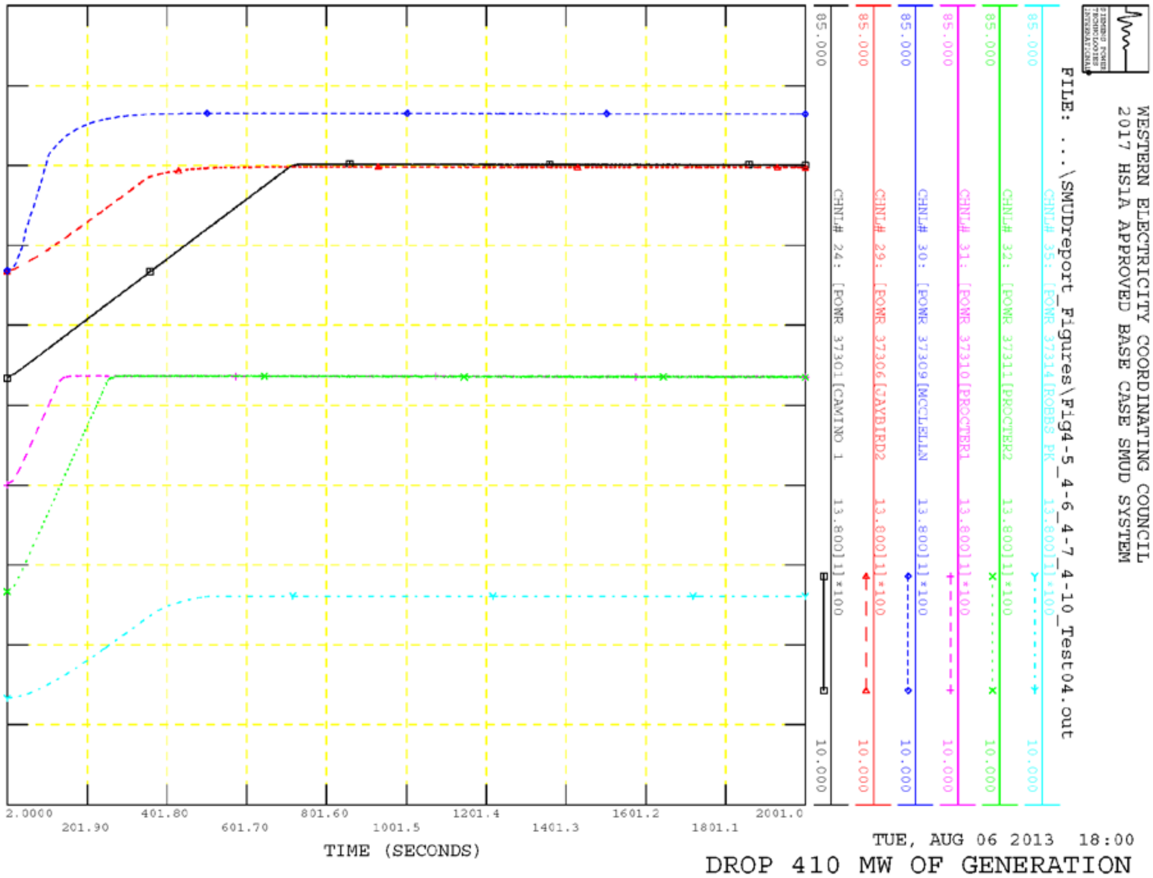


Figure 4-7. Active Power of Some SMUD Units in Response to an Underfrequency Event with All Conventional Units

In the next test, the three units dropped in the previous test were instead ramped down. As before, the total capacity of these three units was 410 MW. These units were ramped down to zero at a rate of about 6.7 MW/sec (ramping period of about 60 seconds). This test may be construed as mimicking the ramping down of renewable power in the SMUD system. For the system as modeled, it represents the loss of approximately 33% of the total generation over a 60 second period, representing, for example, the loss of renewable power with an initial level of renewable penetration of 33% of the total generation.

Figure 4-8 shows the total “renewable power” decreasing from 410 MW to zero. Plots of the system frequency and AGC ACE are shown in Figure 4-9. The time scale of this figure is longer, 5,000 seconds or about 83 minutes. As in the previous test, the remaining 67% of SMUD generation is not able to compensate for the loss of the 410 MW, and the lost generation will be partly supplied by SMUD generation and partly by power coming from the WI equivalent.

Figure 4-10 compares the AGC ACE of two tests, that is, with an instantaneous trip of the 3 generators versus a ramp down over a 60 second period. It can be seen that the AGC response is almost the same, with the only difference being in the first couple of minutes. A slower ramp rate, as might be more representative of wind power change over a distributed area, would have similar results, reducing the first part of the response but not significantly impacting the slower dynamics of the AGC.

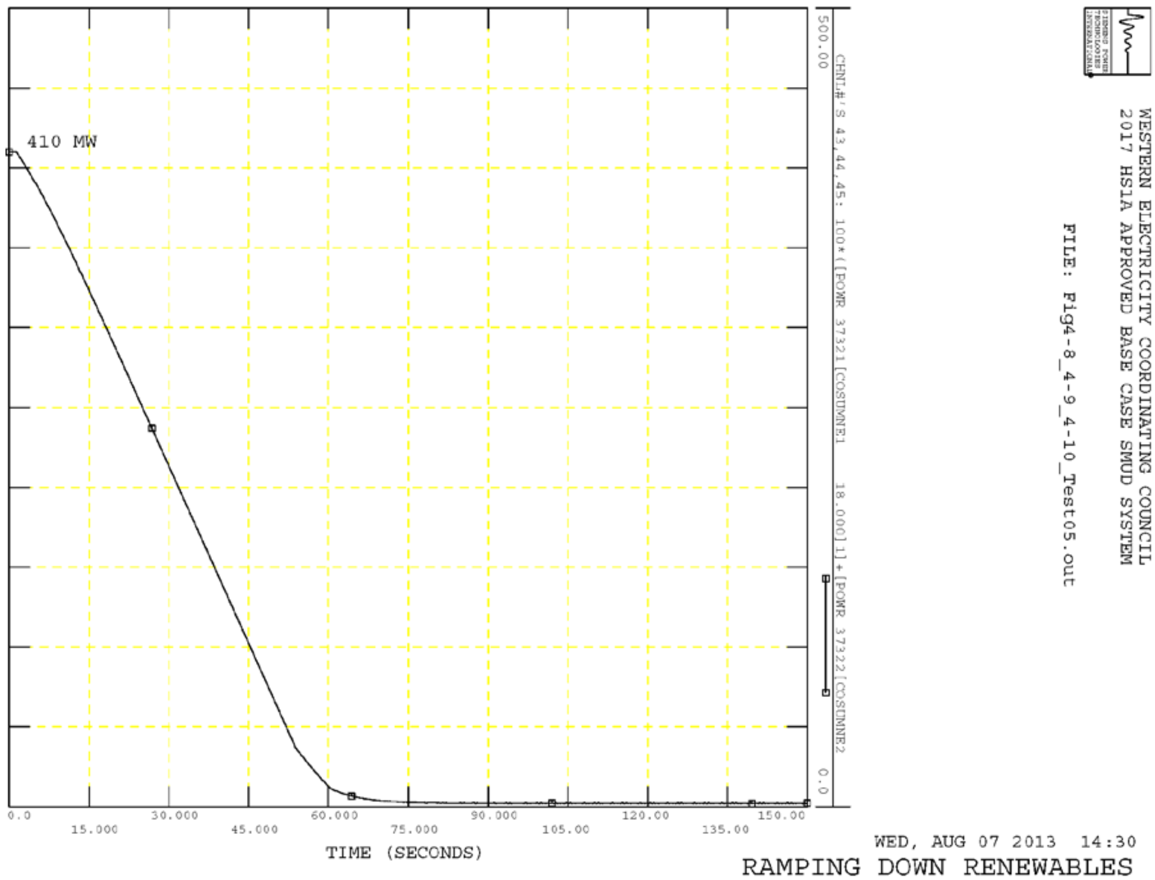


Figure 4-8. Ramp Down of Total "Renewable Power," MW

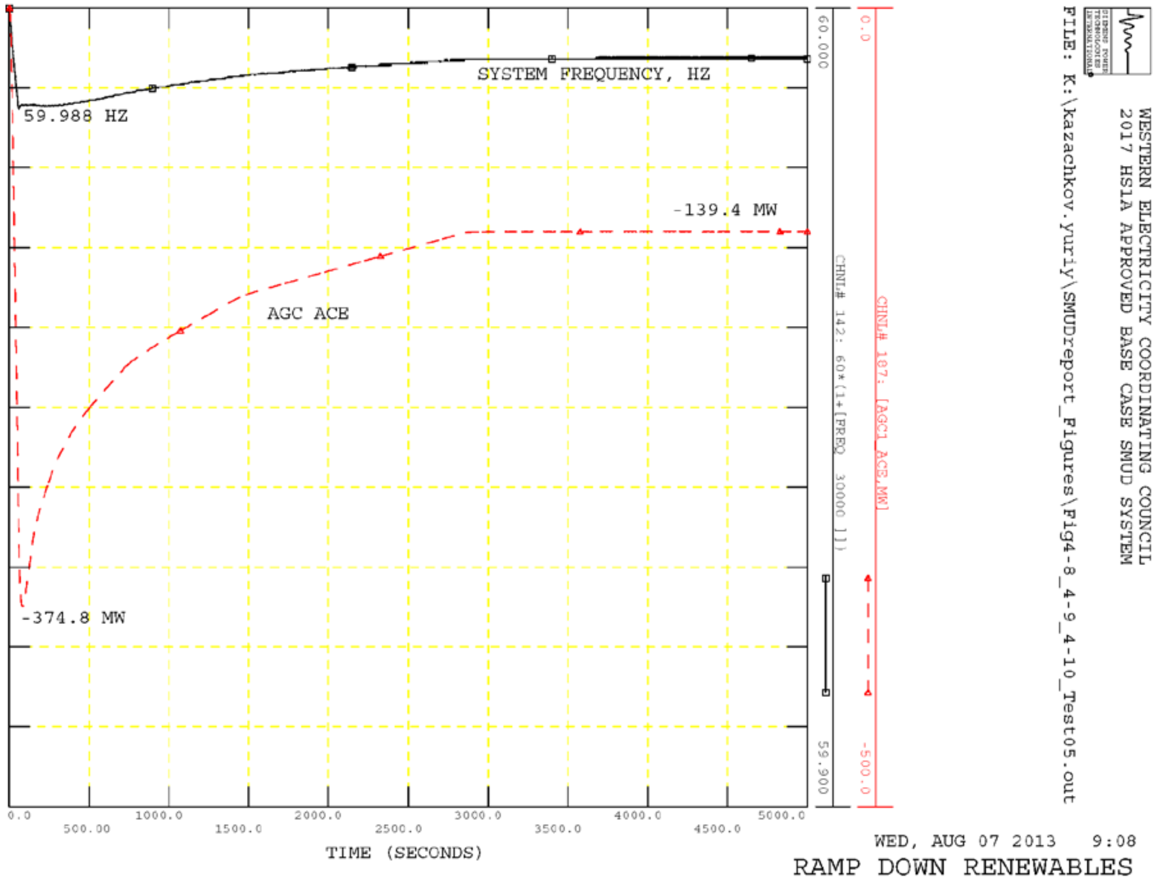


Figure 4-9. System Frequency and AGC ACE in Response to Ramping Down of "Renewable Power" with All Conventional Units

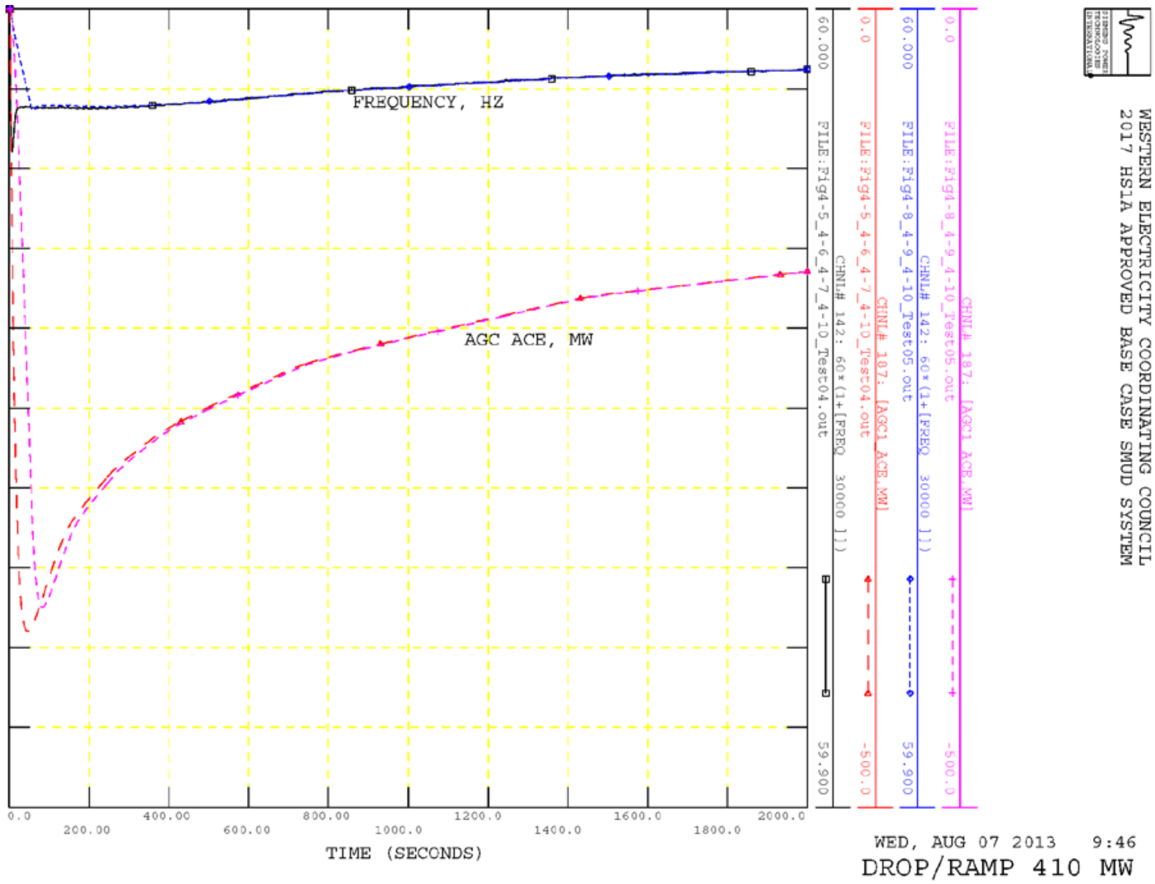


Figure 4-10. Comparing Instantaneous Trip of Generation to the Ramping Down of "Renewable Power" with All Conventional Units

4.3 AGC Response with a Mix of Conventional Generating Units and Adjustable Speed PSH Units

The above simulations demonstrated the characteristics of the AGC response with conventional thermal and hydro units. The replacement of a portion of the conventional hydro turbines in SMUD by AS PSH turbines in generating mode would not have a significant impact on the AGC response, assuming that the AS units have the same maximum and minimum loading and similar ramp rates (long-term ramp rates are primarily a function of the hydraulic design and thus not significantly changed by the adjustable speed design). Thus, the AGC action in response to underfrequency (loss of generation) or overfrequency (drop of load) events would be similar; that is, the main characteristics of the AGC response, the values of ACE and total area interchange, with the advanced hydro turbines will be very similar to that with conventional hydro turbines.

4.4 Existing Conventional Generating Units and Two Conventional Pumps

Although the AGC response of AS PSH units in generating mode will be similar to that of conventional hydro or conventional PSH units of similar hydraulic design, this similarity does not hold true for AS PSH units operating in pumping mode. The regulating abilities of AS PSH units operating in pumping mode are quite different than the capabilities of conventional PSH units.

There are two loads at the Lake substation located close to UARP: one load of 123.5 MW connected to the 69 kV Lake 1 bus and another load of 117 MW connected to the 69 kV Lake 2 bus. These two loads were replaced by conventional hydro pump storage units operating as pumps. Hence, the total generation and load consumption in SMUD remain the same. Note that this is simply a test for illustrating the impact of a PSH in the pumping mode and does not reflect anything representative of actual SMUD operation.

In the first test case, these two pumps were represented by a model of ternary units operating as a pure pump, that is, with the pump operating without the turbine, thus essentially having the characteristics of a conventional PSH unit.

Because conventional pumps do not operate with governor control but rather operate with a constant gate position determined by the operator, the response of the system with pumping load is quite similar to that with other loads of similar magnitude. Figure 4-11 compares frequency and AGC ACE responses to the dropping of 120 MW of SMUD generation with all existing conventional units (as shown in Figure 4-3), and for all existing conventional units and two loads replaced by hydro pumps. The responses are very similar.

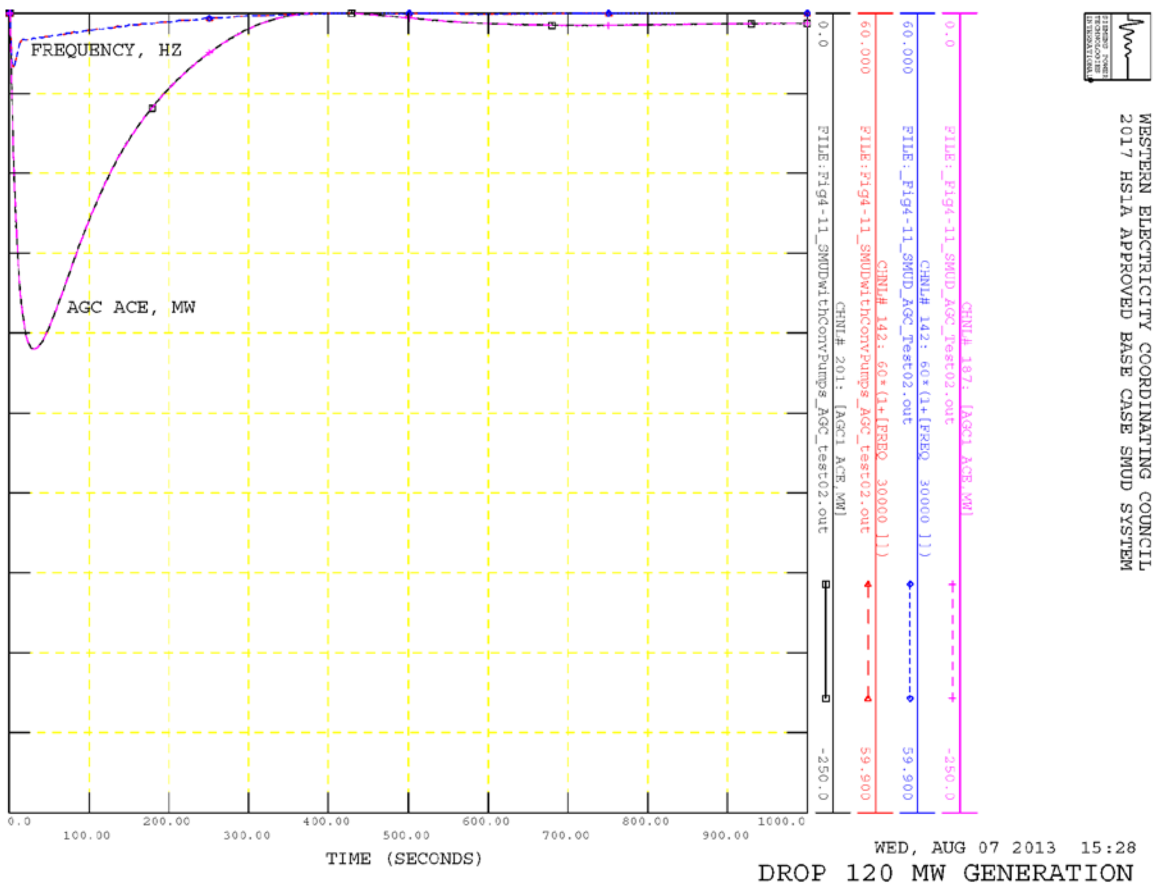


Figure 4-11. System Frequency and AGC ACE in Response to Drop of 120 MW of SMUD Generation for SMUD System with all Existing Conventional Units and Existing Conventional Units and Two Loads Replaced by Hydro Pumps

4.5 Conventional Generating Units and Two Ternary Units in Mixed (Hydraulic Short Circuit) Mode of Operation

Although conventional pumps do not have the ability to respond to AGC, a ternary unit can have this capability. To demonstrate this capability, the same approach to adding two ternary units as in the previous section was used, namely replacing two existing SMUD loads by ternary units, but this time in the mixed (hydraulic short circuit) mode of operation. Again, the total generation and load consumption in SMUD were kept the same.

The diagram in Figure 4-12 depicts the approach used to replace the loads with a ternary unit. The ternary unit that replaced the load of 117 MW connected to the 69 kV Lake 2 bus had a pumping load of 234 MW with the turbine operating at 117 MW, for a net load of 117MW; the unit is thus pumping at 50% of its rating. Thus, assuming that the unit can operate over its whole range, the unit would have the ability to either increase or decrease its output by 117 MW in response to AGC control signals. Dynamic data for the ternary pump model and for the AGC model are provided in Appendix B, Figures B-3 and B-4.

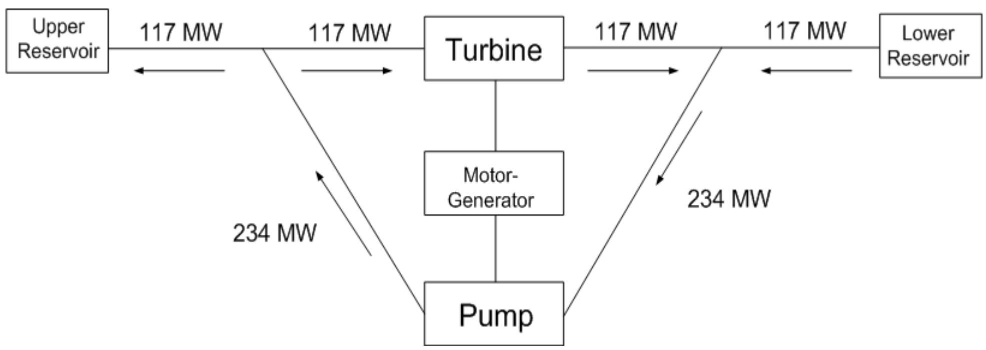


Figure 4-12. Ternary Unit in the Hydraulic Short Circuit Mode of Operation

Figure 4-13 compares the frequency and AGC ACE in response to the dropping of 410 MW of generation in SMUD with all conventional generating units and two conventional pumps and the SMUD system with all conventional generating units and two ternary units in the mixed mode of operation as described above. Figure 4-13 clearly shows a significant difference in frequency and AGC ACE in response, with the ternary units able to significantly improve the response of the AGC controls. Note that, as described above, the loss of 410MW of generation is larger than the regulating capability of the SMUD system as modeled and hence the AGC system cannot return frequency and ACE to their original values. However, the extra regulating capability with the ternary units results in a larger and improved response. This is illustrated by the plots of SMUD's total mechanical power in Figure 4-14, which clearly show that the ternary units significantly contribute to AGC action.

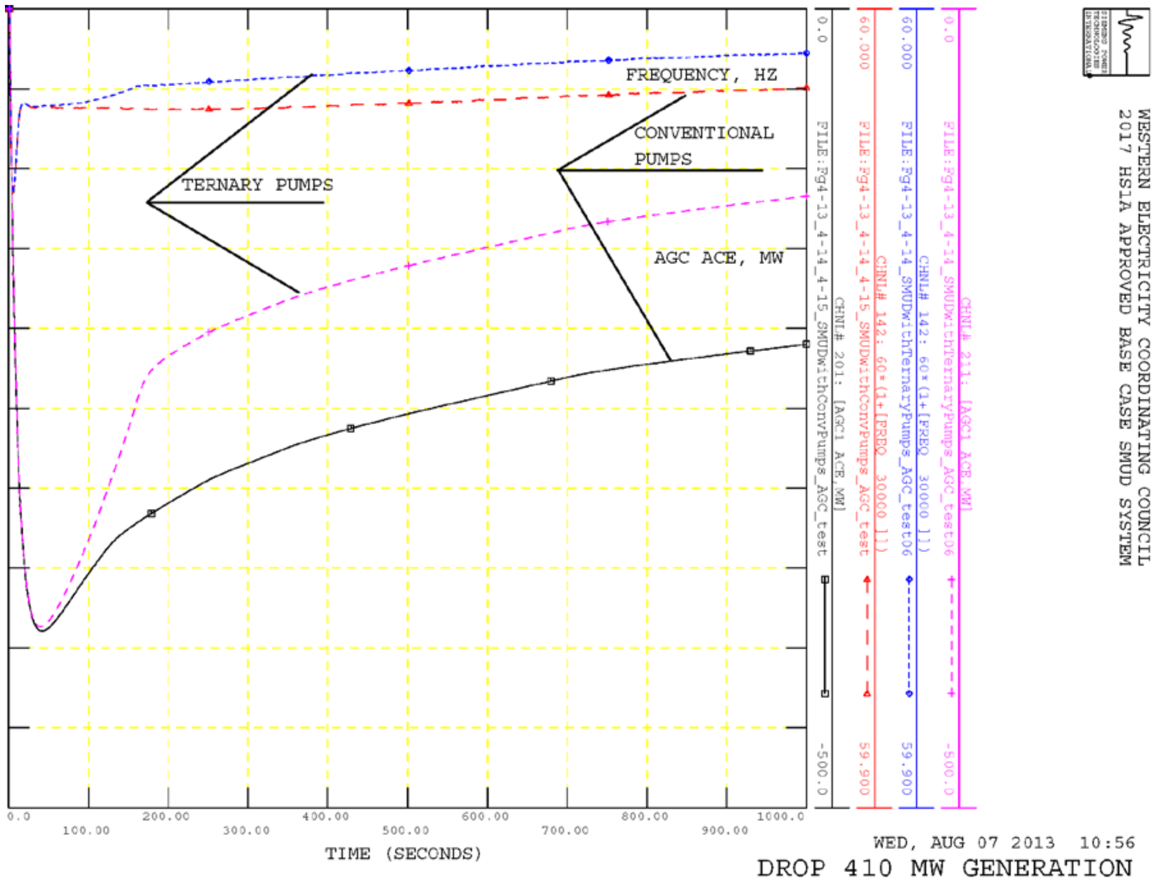


Figure 4-13. Frequency and AGC ACE in Response to Drop of 410 MW of SMUD Generation with Conventional Generation and Two Conventional Pumps Versus SMUD System with Conventional Generation and Two Ternary Units in Pumping Mode

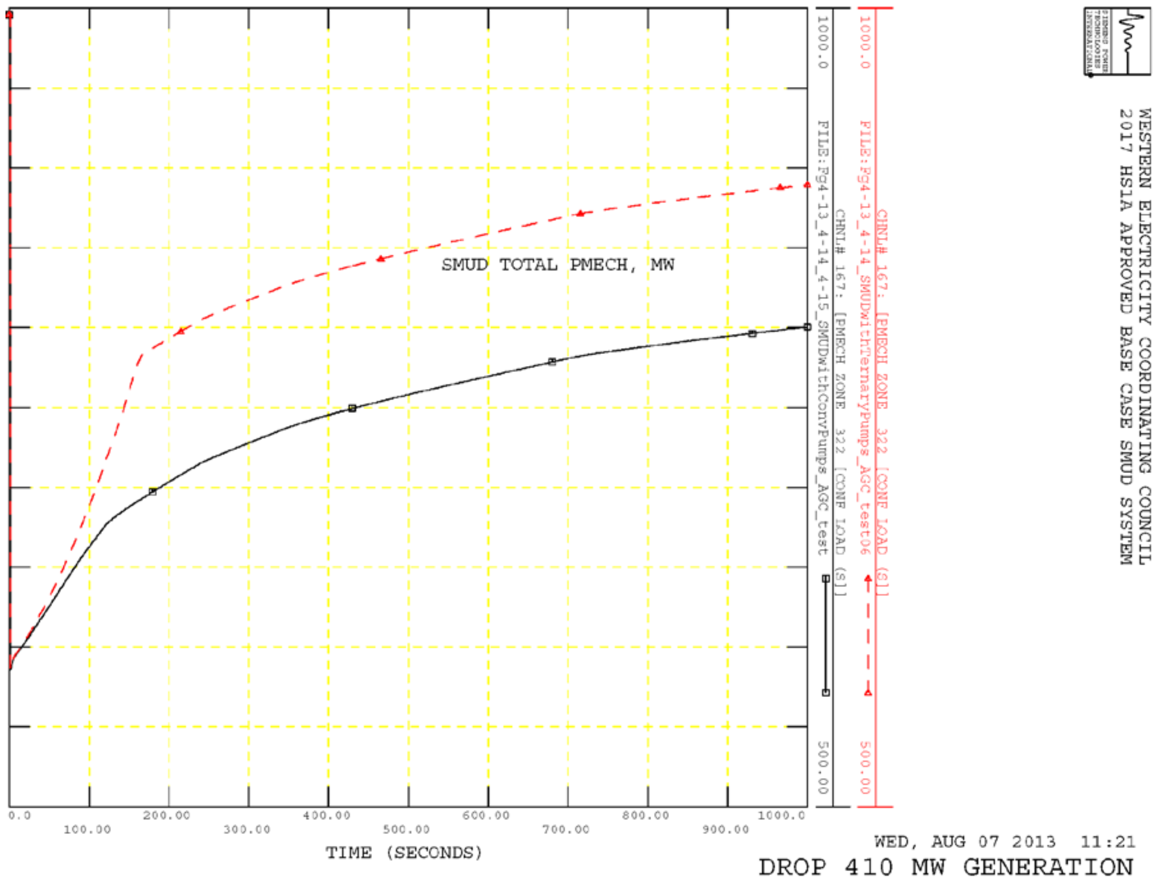


Figure 4-14. Total SMUD Mechanical Power in Response to Drop of 410 MW of SMUD Generation with Conventional Generation and Two Conventional Pumps Versus SMUD System with Conventional Generation and Two Ternary Units in Pumping Mode

4.6 Existing Conventional Generating Units and Two Adjustable Speed Pumps

Adjustable speed PSH units also have the ability to contribute to frequency regulation during the pumping mode of operation. The same approach to adding two adjustable speed pumps as in the previous section was used, namely replacing two existing SMUD loads by adjustable speed pumps. Again, the total generation and load consumption in SMUD remain the same.

The dynamic data for the AS pump model and for the AGC model are provided in Appendix B, Figures B-5 and B-6.

The very fast, virtually instantaneous from the AGC bandwidth standpoint, response of the AS DFIM based unit requires careful tuning of the control parameters of the AS pump and AGC, including power ramping rates, rotor speed reference limits, AGC regulation contribution coefficients, etc. Although the fast AS controls can be used to impact transient stability response, the AGC response of the AS pumps will be a function of the hydraulic system and thus will have ramp rates in the same range in pumping as in generating mode. However, the very fact that AS pumps can participate in AGC could be quite important.

Figure 4-15 compares the system response to the dropping of 410 MW of generation in SMUD for two scenarios: with all conventional generating units and two conventional pumps and with all conventional generating units and two AS pumps. Figure 4-15 shows some improvement in the AGC ACE response with the AS pumps versus with the conventional pumps. It is expected that the controls of the AS pumps could be better optimized to improve performance over that shown in Figure 4-15.

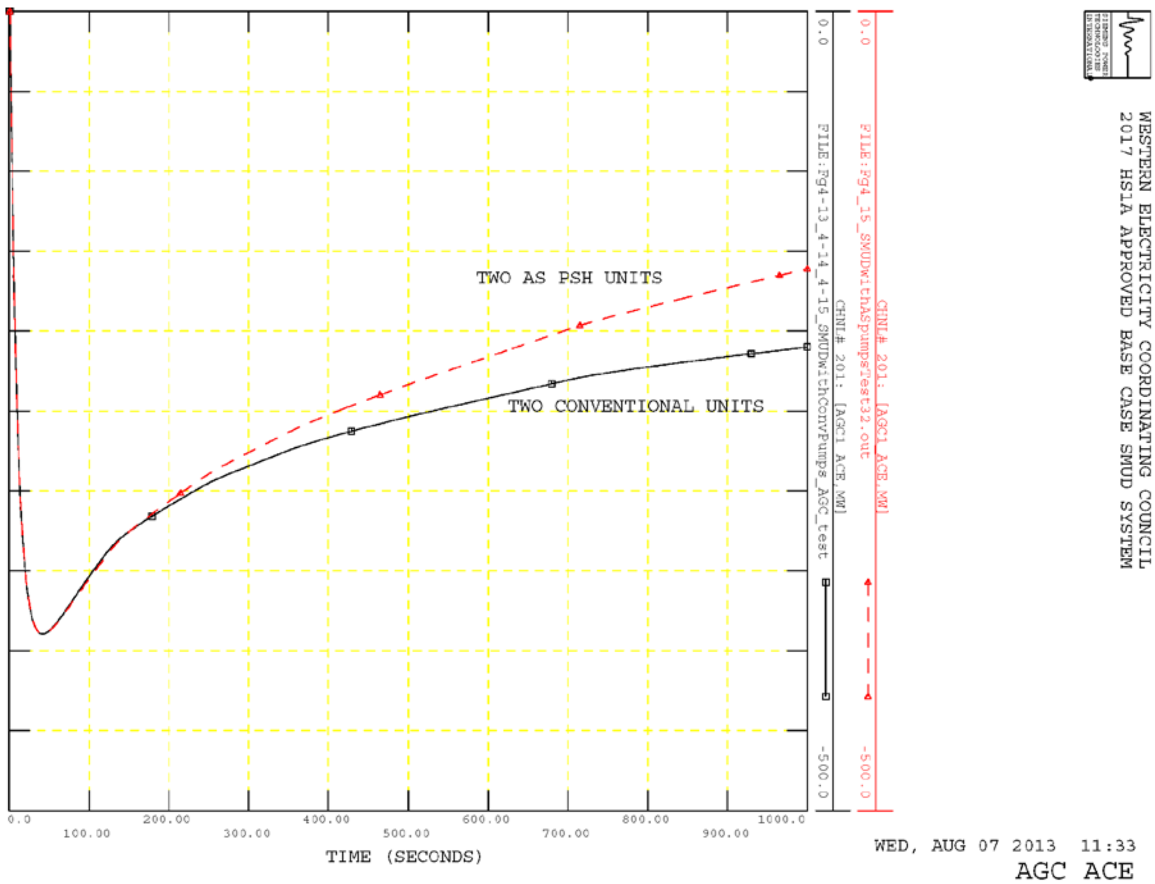


Figure 4-15. AGC ACE in Response to Drop of 410 MW of SMUD Generation for SMUD System with Conventional Generation and Two Conventional Pumps Versus with Conventional Generation and Two AS PSH Pumps

4.7 SMUD with the Iowa Hill Plant Employing AS PSH units

The proposed Iowa Hill plant will use three 133 MW generating units. The project description[3] notes four primary expected advantages of using adjustable speed machines versus conventional synchronous alternatives:

1. Lowering the system disturbance due to pumping starts.
2. The ability to operate at part load during the pumping mode facilitates the ability to optimize purchase of pumping power or operation of SMUD-owned resources to provide pumping, resulting in lower overall system costs.
3. The units could be used for regulation while in pumping mode, reducing the need for other regulating resources while pumping.
4. Providing additional flexibility to otherwise lower overall system costs.

Here we will discuss and illustrate the third advantage listed above, that is, the ability of the AS PSH units to participate in secondary frequency control. This ability to participate in secondary frequency control will be demonstrated for the situation when an abrupt increase in the wind power occurs.

Using the same equivalent as described in Figure 2-2, an additional power plant was added to represent an increase in wind generation. This plant was connected to the Hurley 230 kV bus number 37010. Initially, this plant is dispatched with zero power but has the MVA capability sufficient to accommodate ramping up its output to 400 MW. This 400 MW represents about 32% of the total generation in the SMUD area, as modeled in the WECC 2017 summer peak case.

According to the project description, the Iowa Hill plant will be connected to a tap of the 230kV line between Camino and White Rock as shown in Figure 4-16. All three units are dispatched as pumps consuming 27 MW or about 20% of their rated power. (Note that this is for illustrative purposes and should not be construed to represent a suggested or planned operating point.)

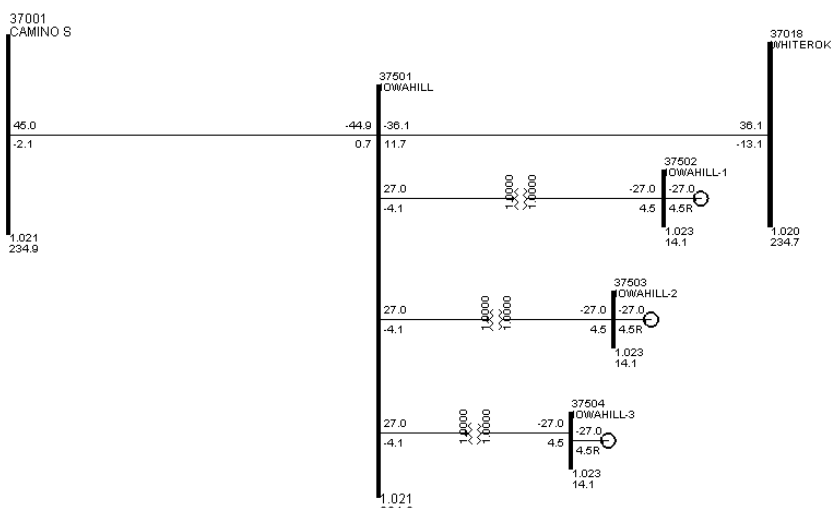


Figure 4-16. Iowa Hill Plant Arrangement

[3] Iowa Hill Project Description, SMUD, November 2003.

In the first test case, the three Iowa Hill units are modeled as conventional pump storage units. As such, these units do not participate in secondary frequency (AGC) control. All of the other 22 SMUD units modeled are controlled by the AGC as in previous simulations.

Initially, there is a 1,939 MW power flow from WECC to SMUD. The additional power plant that was added on bus 37010 to represent an increase in wind was ramped from 0 to 400 MW over 50 seconds (i.e., at 8 MW/sec), as shown in Figure 4-17.[4] As a result of the increasing wind generation, the power flow on the SMUD tie lines will go down. AGC will try to restore the initial tie flow by reducing the power outputs of all SMUD machines controlled by the AGC. Because in this simulation the Iowa Hill units are modeled as conventional pumps, they are not controlled by the AGC. Note that there is only a small change in frequency reflected in the AGC ACE due to the size of the WECC system; hence, the AGC controls are primarily controlling tie-line flow.

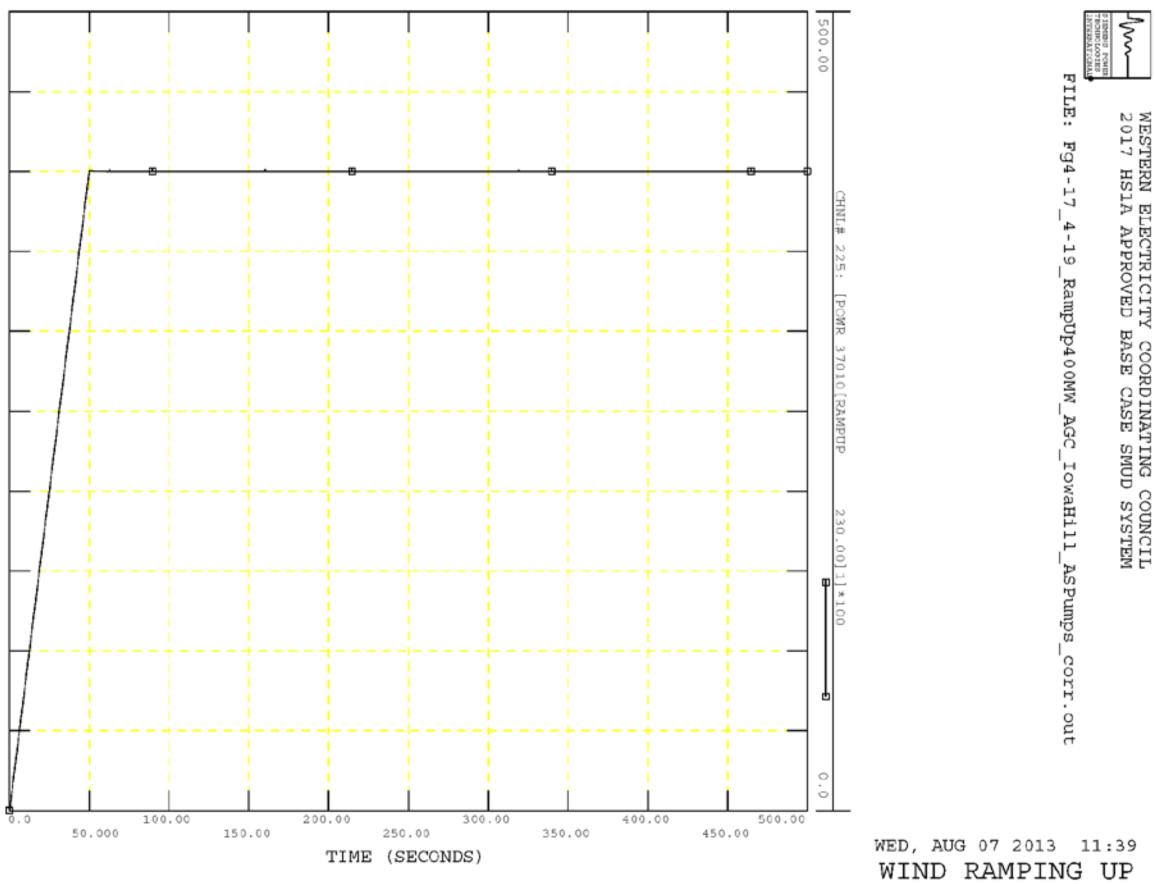


Figure 4-17. Ramp Up of Wind Power in the SMUD Area

Figure 4-18 shows the AGC ACE, total tie-line flow, and the system frequency in response to the wind power ramping up with the Iowa Hill units operating as conventional pumps. The available margin for reduction of the power outputs of the SMUD generating units was not

[4] Note that this ramp rate is also for illustrative purposes and should not be construed to represent a typical or expected change in wind generation.

sufficient to reducethe AGC ACE error to zero and to restore the tie-line flow to its original value.

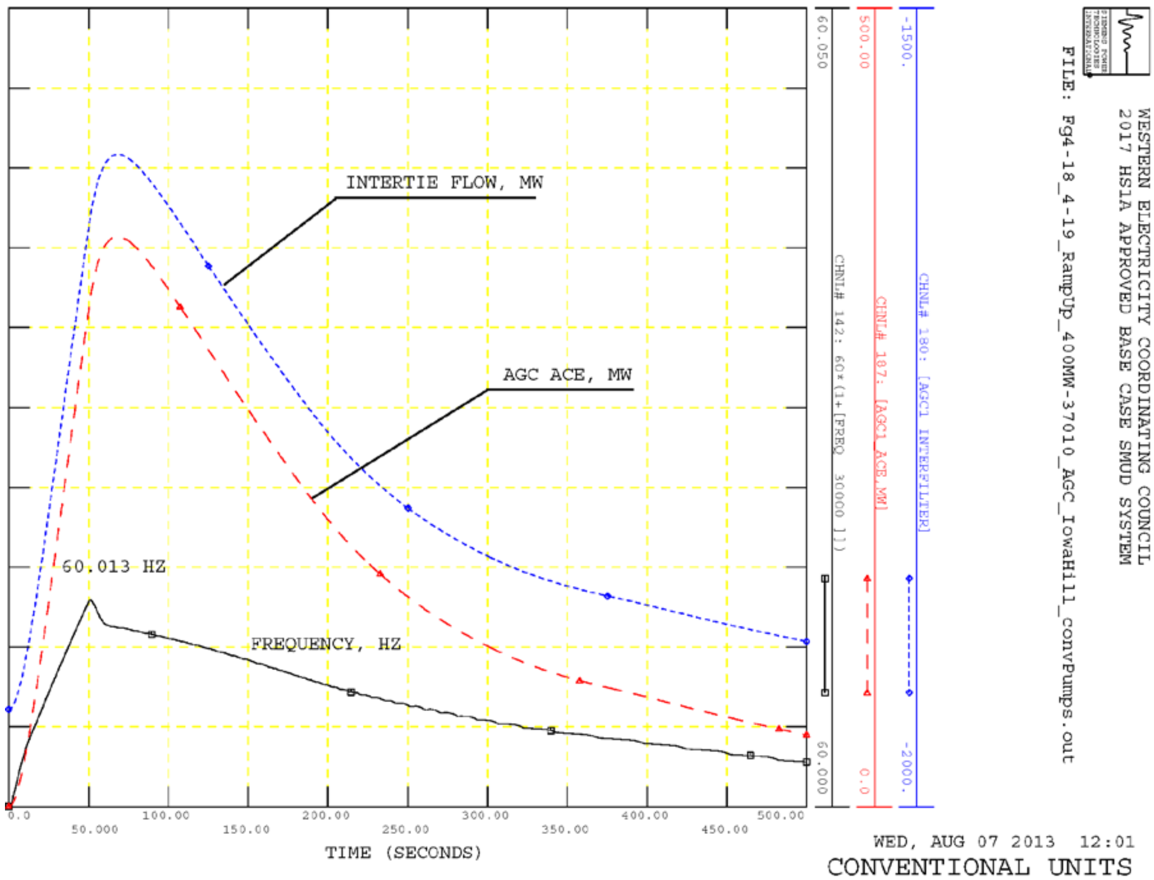


Figure 4-18. AGC ACE (red), Total Tie-Line Flow (blue), and System Frequency (black) in Response to Wind Power Ramping Up with the Iowa Hill Units Operating as Conventional Pumps

In the next simulation, the Iowa Hill units were modeled as AS pumps. Figure 4-19 compares the response with the Iowa Hill units modeled as both conventional pumps and AS pumps. The quantities shown are the Iowa Hill pump output and the total tie-line flow. One can see that AGC action results in reduction of the AS pump input power from −27 MW to −46 MW for each of the three units. This improves the AGC performance. As noted previously, the AS pump controls are not optimized, and it is likely that the units could be made more responsive to AGC control action.

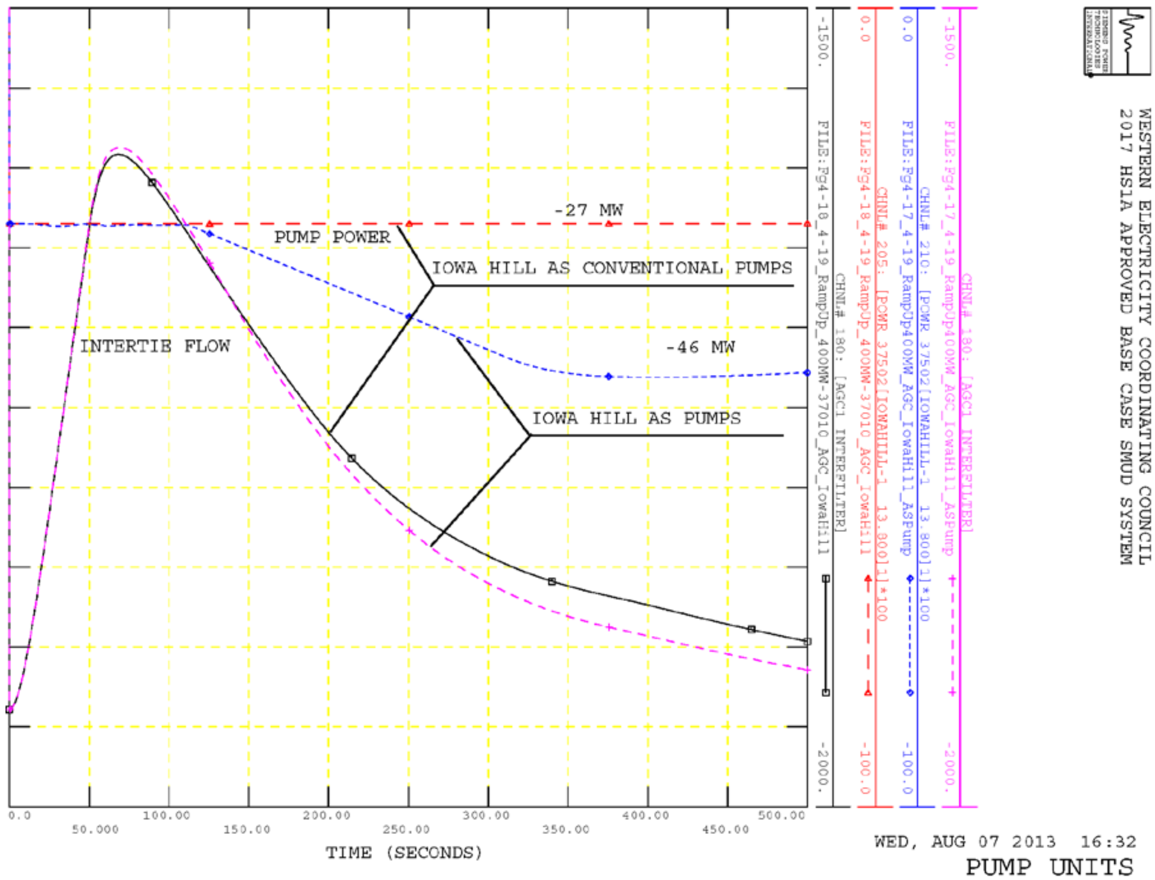


Figure 4-19. Iowa Hill Pump Input Power (red and blue) and Total Tie-line Power (black and pink) with Conventional (black and red) and AS (pink and blue) Pumps at Iowa Hill in Response to Wind Power Ramping Up

The same set of simulations was run using load values representing a 2022 light load condition. The information regarding loads and generation was received from the PLEXOS model used in another task of the DOE project. The SMUD load and generation of the 2017case were scaled down to 2,100 MW and 774 MW, respectively. Due to the lighter load, seven machines in SMUD were turned off, and thus the number of machines contributing to the AGC is reduced. The initial tie-line flow from the WI to SMUD in this light load case is 1,337 MW, compared to 1,860 MW in the 2017 summer peak case. The same disturbance, namely ramping up the wind power to 400 MW, was used. Note that 400 MW now represents about 47% of the on-line SMUD generation.

The response of AGC ACE, total tie-line flow, and system frequency to the wind power ramping up with the Iowa Hill units operating as conventional pumps are shown in Figure 4-20. The available margin for reduction of the power outputs of the SMUD generating units was sufficient to reduce the AGC error to zero and to restore the tie-line flow to its original value.

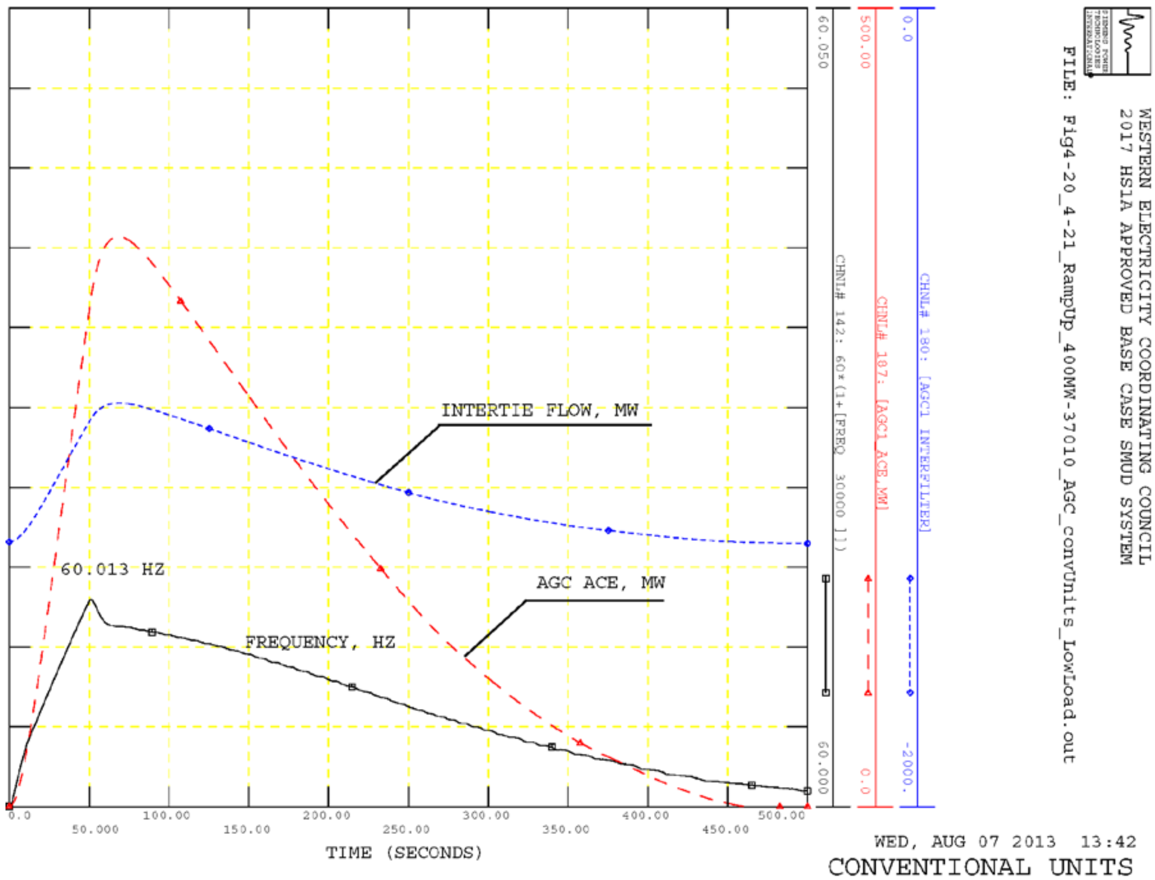


Figure 4-20. AGC ACE (red), Total Tie-Line Flow (blue), and System Frequency (black) in Response to Wind Power Ramping Up with Iowa Hill Units Operating as Conventional Pumps for the 2022 Light Load System Conditions

Figure 4-21 compares the response of the Iowa Hill pump output and the total tie-line flow for conventional and AS pumps modeled at Iowa Hill for the light load case. AGC action results in a reduction of the AS pump input power from −27 MW to −52 MW. For this specific example, it did not noticeably affect the secondary control because the AGC control action was adequate even with conventional pumps at Iowa Hill. However, for some applications, the AS PSH unit's capability to change the input power while pumping could be essential.

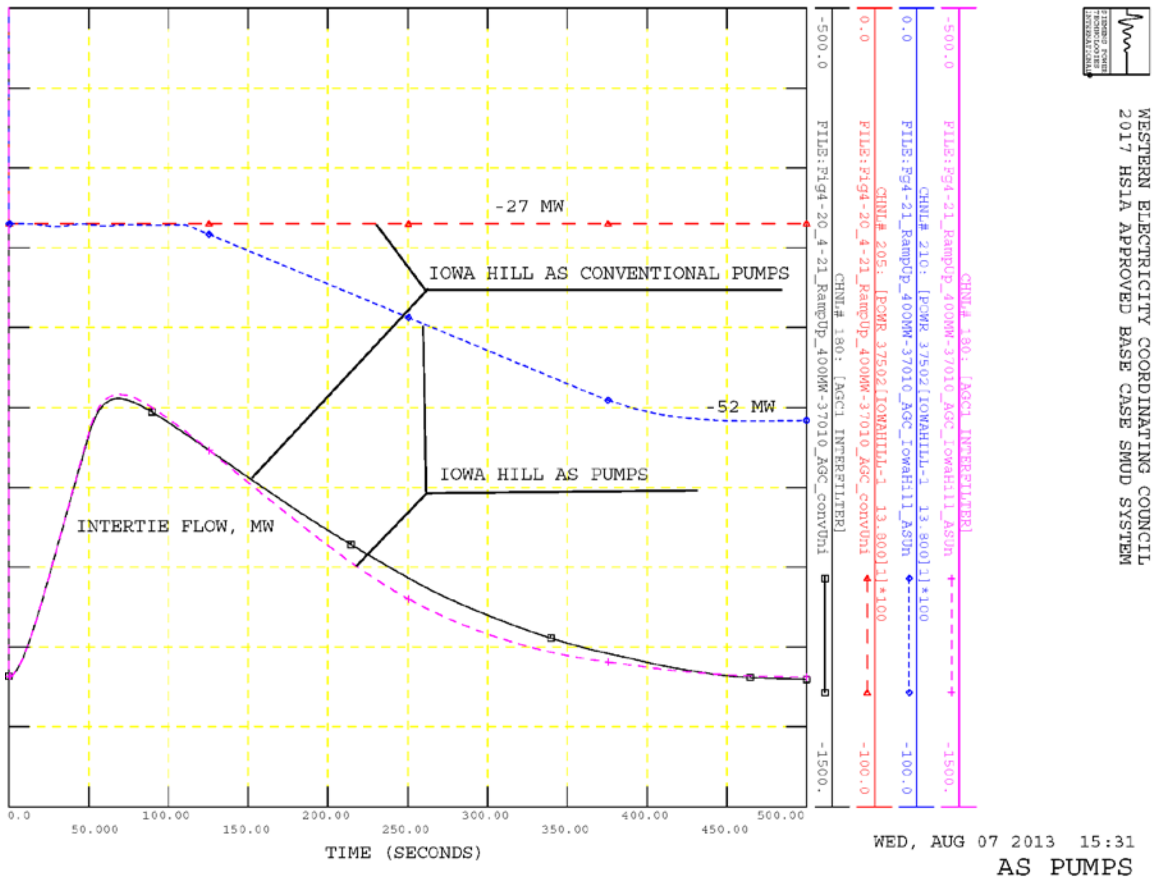


Figure 4-21. Iowa Hill Pump Input Power (red and blue) and Total Tie-Line Flow (black and pink) with Conventional (black and red) and AS (pink and blue) Pumps at Iowa Hill in Response to Wind Power Ramping Up for the 2022 Light Load System Conditions

Section 5

Conclusions

A variety of simulations were performed using a system based roughly on the Sacramento Municipal Utility District power. The intent was to use the SMUD system, as a typical balancing authority and project team member, to test the models of the advanced pump storage hydro technology newly developed in the course of the DOE project and to demonstrate the potential benefits of this technology.

The SMUD component of a 2017 Summer Peak Load Western Interconnection (WI) case and a 2022 Light Load WI case were used in the analysis. The SMUD AGC system was approximated by a dynamic simulation model and added to the above representations to add the capability to control not only conventional generating units whose prime movers are simulated by standard PSS®E turbine-governor models but also the newly developed models of the advanced pump storage hydro units.

The disturbances used to demonstrate AGC performance included the following:

- Dropping of generating units of different sizes in SMUD
- Ramping down the generation in SMUD
- Ramping up generation in SMUD.

These two latter disturbances can be construed to represent a change in renewable power, for example, a drop or an increase in wind or solar generation power.

The simulations showed that the advanced pump storage technologies can improve secondary frequency control capabilities. The advantages of both ternary and adjustable speed technologies were demonstrated.

The proposed Iowa Hill pumped storage hydro plant was also added to the SMUD system. Its three AS PSH units were tested as pumps for two WI system conditions, namely the 2017 summer peak load case and 2022 light load case. Wind power ramping up from zero to 400MW was used as a disturbance.

For all of these scenarios and disturbances, the newly developed models of AS PSH units and ternary units showed expected performance and allowed demonstration of the expected advantages of the advanced PSH technology, specifically the capability of AS pumps and ternary pumps to participate in the secondary (AGC) control.

This page intentionally left blank.

Section

6

References

1. Review of Existing Hydroelectric Turbine-Governor Simulation Models, Report, Argonne National Laboratory, ANL/DIS-13/05, August 2013.

2. Modeling Adjustable Speed Pumped Storage Hydro Units Employing Doubly-Fed Induction Machines, Report, Argonne National Laboratory, ANL/DIS-13/06, August 2013.

3. Modeling Ternary Pumped Storage Units, Report, Argonne National Laboratory, ANL/DIS-13/07, August 2013.

4. Testing Dynamic Simulation Models for Different Types of Advanced Pumped Storage Hydro Units, Report, Argonne National Laboratory, ANL/DIS-13/08, August 2013.

This page intentionally left blank.

Appendix

A

Datasheet of the Automatic Generation Control (AGC) Model

Table A-1 provides a description of the parameters of the Automatic Generation Control (AGC) model.

Table A-1. AGC01 Model Parameters

ICON	#	Description
M		=1: AGC on, =0: AGC off Note: INTICN(M) stores the STATUS of the model
M+1	NTIE	Number of tie lines
M+2	NDM	Number of designated generating units
M+3		ACE Contribution to Economy Flag
M1=M+4		First line From bus
M1+1		First line To bus
M1+2		First line CKTID
……..	………	…………………………………………………………
M1+3*(NTIE-1)		Last line From bus
M1+1+3*(NTIE-1)		Last line To bus
M1+2+3*(NTIE-1)		Last line CKTID
M2=M1+3+3*(NTIE-1)= M1+3*NTIE		First designated unit bus #
M2+1		First designated unit ID
M2+2		First designated unit control switch: 0 – Base, 1 – Base & Regulated, 2 - Automatic
…………….	………..	…………………………………………………………
M2+ 3*(NDM-1)		Last designated unit bus #
M2+1+3*(NDM-1)		Last designated unit ID
M2+2+3*(NDM-1) = M+3+3*NTIE+3*NDM		Last designated unit control switch: 0 – Base, 1 – Base & Regulated, 2 - Automatic

Table A-1. AGC01 Model Parameters (cont.)

CON	#	Description
J		BF, Frequency Bias, MW/0.1Hz
J+1		Kace, ACE gain
J+2		K1, emergency ACE deadband, MW
J+3		Flim, upper permissible frequency, Hz
J+4		Tf, frequency filter time constant, sec.
J+5		Ti, power interchange filter time constant, sec.
J+6		Tace, ACE filter time constant, sec.
J+7		Tsum, Total actual power filter time constant, sec.
J1=J+8		RF_1, First Unit Regulating Factor
J1+1		AF_1, First Unit Emergency Regulating Factor
J1+2		Tlead, First Unit lead time constant, sec.
J1+3		Tlag, First Unit lag time constant, sec.
J1+4		RPup, First unit up power rate limit, MW/min.
J1+5		RPdown, First unit down power rate limit, MW/min.
J1+6		Pmax, First unit max power limit, MW
J1+7		Pmin, First unit min power limit, MW
J1+8		EPF, First unit economic participation factor
J1+9		Tpact, First unit Pact filter, sec.
……………….	………	……………………………………………………..
J1+10*(NDM-1)		RF, Last Unit Scaling Factor
J1+1+10*(NDM-1)		AF, Last Unit Emergency Scaling Factor
J1+2+10*(NDM-1)		Tlead, Last Unit lead time constant, sec.
J1+3+10*(NDM-1)		Tlag, Last Unit lag time constant, sec.
J1+4+10*(NDM-1)		RPup, Last unit up power rate limit, MW/min.
J1+5+10*(NDM-1)		RPdown, Last unit down power rate limit, MW/min.
J1+6+10*(NDM-1)		Pmax, Last unit max power limit, MW
J1+7+10*(NDM-1)		Pmin, Last unit min power limit, MW
J1+8+10*(NDM-1)		EPF, Last unit economic participation factor
J1+9+10*(NDM-1)= J+7+10*NDM		EPF, Last unit Pact filter, sec.

Table A-1. AGC01 Model Parameters (cont.)

STATE	#	Description
K		Frequency filter
K+1		Interchange filter
K+2		ACE Filter
K+3		Total actual power filter
K1=K+4		First unit actual power filter
K1+1		First unit lead-lag
K1+2		First unit dPset
…………….	………	…………………………………………………………..
K1+3*(NDM-1)		Last unit actual power filter
K1+1+3*(NDM-1)		Last unit lead-lag
K1+2+3*(NDM-1)= K+3+3*NDM		Last unit dPset

Table A-1. AGC01 Model Parameters (cont.)

VAR	#	Description
L		ACE, area control error, MW
L+1		dTie, interchange power deviation, MW
L+2		Is, Interchange schedule, MW
L+3		Ia, actual interchange, MW
L+4		Ptie storage, MW
L+5		Total Pact
L+6		Total Pbase
L1=L+7		$Pref_0$, first unit initial governor speed reference, pu on MBASE
L1+1		PE, first unit economic contribution
L1+2		dPREG , first unit desired power increment, MW
L1+3		dPEA, first unit emergency power increment, MW
L1+4		BASE, first unit electrical power reference, MW
L1+5		MUCE, first unit lead/lag output, MW
L1+6		Pset, first unit output, pu on MBASE
………………	………..	………………………………………………………………
L1+7*(NDM-1)		$Pref_0$, last unit initial governor speed reference, pu on MBASE
L1+1+7*(NDM-1)		PE, last unit economic contribution
L1+2+7*(NDM-1)		dPREG, last unit desired power increment, MW
L1+3+7*(NDM-1)		dPEA, last unit emergency power increment, MW
L1+4+7*(NDM-1)		BASE, last unit electrical power reference, MW
L1+5+7*(NDM-1)		MUCE, last unit lead/lag output, MW
L1+6+7*(NDM-1) =L+6+7*NDM		Pset, last unit output, pu on MBASE

```
Number of ICONs  = NM = 4+3*(NTIE+NDM)
Number of CONs   = NC = 8+10*NDM
Number of STATEs = NS = 4+3*NDM
Number of VARs   = NV = 7+7*NDM
   0   'USRMDL'  0  'AGC01'  8  0  NM  NC  NS  NV
                            List of NM ICONs
                            List of NC CONs /
```

Appendix

B

Dynamic Data Documentation

Tables B-1 through B-6 provide documentation of the dynamic data used in the modeling effort.

```
REPORT FOR PLANT MODELS                   BUS 30000 [SYSTEM      230.00] MODELS

 ** GENROU **  BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S
            30000 SYSTEM       230.00 1     317-330       135-140

            MBASE     Z S O R C E         X T R A N       GENTAP
         210900.0  0.00000+J 0.16800  0.00000+J 0.00000  1.00000

  T'D0 T''D0  T'Q0 T''Q0     H   DAMP   XD     XQ     X'D    X'Q   X''D    XL
  7.40 0.034  0.68 0.099   4.82  0.00 2.2800 2.1700 0.2330 0.6400 0.1680 0.1300
                                S(1.0)  S(1.2)
                                0.0300  0.4000


 ** EXBAS **   BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S
            30000 SYSTEM       230.00 1     806-826       274-280

    TR       KP       KI       KA       TA       TB       TC     VRMAX    VRMIN
  0.030    1.000    0.000   41.600    0.100    0.500    1.500    6.000   -5.500

    KF       TF      TF1      TF2       KE       TE       KC       KD
  0.020    3.500    0.000    0.010    1.200    0.089    0.000    0.000

                    E1      S(E1)     E2      S(E2)
                  6.0000   0.1000   7.0000   0.3300


 ** TGOV4 **   BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S     V A R S     I C O N S
              30000 SYSTEM       230.00 1    1484-1535      491-507        262-287      50-56

     K       T1       T2       T3       UO       UC      KCAL      T4       K1      T5
   20.00    0.080    0.000    0.150    0.177   -1.770    1.000    0.200    0.310   9.000

     K2       T6     PRMAX      KP       KI     TFUEL    TFD1     TFD2      KB      CB
   0.260    0.350    1.100    0.010    0.000    0.000    0.000    0.000    0.9001000.00

    TIV     UOIV     UCIV       R    OFFSET CV DM CH    CV2      CV3      CV4 IV DMCH
   0.250    0.100  -10.000    0.050    0.400    0.800    0.000    0.000    0.000  0.200

    IV2   CV CHAR IV CHAR CV STRT CV RATE CV TIM1 CV TIM2 CV TIM3 CV TIM4 IVSTRT
   0.000    0.800    0.200    0.100    4.000    0.500    0.000    0.000    0.000  0.100

  IVRATE IV TIM1 IV TIM2   TRPLU PLU RLV   TIMER PLU ULV   TREVA EVA RLV EVAULV
  10.000    0.500    0.000    0.050    1.000    0.050    1.000    0.000    0.000  0.000

  MIN LR   R RATE           # CV     # IV    PLU/EVA

   0.400    0.100              1        1        0
```

Figure B-1. Dynamic Data of the Equivalent Unit Representing the Western Interconnection

```
 ** AGC01 **     I C O N S      C O N S     S T A T E S     V A R S
                   57-162      1480-1707      488-557       286-446

    AGC FLAG  NTIE    NDM    ACE/ECONOMY
        1      12      22       0

  (---------------    AGC CONSTANTS - MAIN CONTROL   -------------------)
      BF       Kace      K1      lim       Tf       Ti      Tace     Tsum
    81.000    1.000 1000.000   10.000    5.000   10.000   10.000   10.000

    (-------- TIE LINES --------)
    FROM BUS      TO BUS    CKTID
     37005        30000      '1 '
     37005        30000      '2 '
     37010        30000      '1 '
     37010        30000      '2 '
     37010        30000      '3 '
     37010        30000      '4 '
     37012        30000      '1 '
     37012        30000      '2 '
     37013        30000      '1 '
     37016        30000      '1 '
     37016        30000      '2 '
     37021        30000      '2 '

    MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
       37310      '1 '         2               97-     99    1488-  1497     492-    494     293-    299
     RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
    2.700    0.120   10.000   20.000    5.000   -5.000   50.000   10.000    1.000    1.000

    MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
       37312      '1 '         2              100-    102    1498-  1507     495-    497     300-    306
     RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
    2.700    0.120   10.000   20.000    5.000   -5.000   50.000   10.000    1.000    1.000

    MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
       37313      '1 '         2              103-    105    1508-  1517     498-    500     307-    313
     RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
    3.500    0.120   10.000   20.000   10.000  -10.000   50.000   10.000    1.000    1.000

    MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
       37315      '1 '         2              106-    108    1518-  1527     501-    503     314-    320
     RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
    2.950    0.120   10.000   20.000    5.000   -5.000   50.000   10.000    1.000    1.000

    MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
       37315      '2 '         2              109-    111    1528-  1537     504-    506     321-    327
     RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
    1.290    0.120   10.000   20.000    5.000   -5.000   15.000    0.000    1.000    1.000

    MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
       37316      '1 '         2              112-    114    1538-  1547     507-    509     328-    334
     RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
    2.950    0.120   10.000   20.000    5.000   -5.000   50.000   10.000    1.000    1.000

    MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
       37320      '1 '         2              115-    117    1548-  1557     510-    512     335-    341
     RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
    1.327    0.120   10.000   20.000    5.000   -5.000   25.000    0.000    1.000    1.000

    MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
       37321      '1 '         2              118-    120    1558-  1567     513-    515     342-    348
     RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   11.500    0.120   10.000   20.000    5.000   -5.000  200.000   50.000    1.000    1.000

    MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
       37322      '1 '         2              121-    123    1568-  1577     516-    518     349-    355
     RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   11.500    0.120   10.000   20.000    5.000   -5.000  200.000   50.000    1.000    1.000
```

Figure B-2. Dynamic Data Documentation of the SMUD System AGC Model with the 22 Original Generating Units

```
 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37323      '1 '        2                124-    126    1578-   1587     519-    521     356-    362
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
11.200    0.120   10.000   20.000   10.000  -10.000  200.000   50.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37301      '1 '        2                127-    129    1588-   1597     522-    524     363-    369
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 3.700    0.120   10.000   20.000    1.700   -1.700   70.000   10.000    1.000    1.000
 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37302      '1 '        2                130-    132    1598-   1607     525-    527     370-    376
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 3.700    0.120   10.000   20.000    1.700   -1.700   70.000   10.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37305      '1 '        2                133-    135    1608-   1617     528-    530     377-    383
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 3.700    0.120   10.000   20.000    1.700   -1.700   70.000   10.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37306      '1 '        2                136-    138    1618-   1627     531-    533     384-    390
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 3.800    0.120   10.000   20.000    1.700   -1.700   70.000   10.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37309      '1 '        2                139-    141    1628-   1637     534-    536     391-    397
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 4.050    0.120   10.000   20.000   10.000  -10.000   75.000    0.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37314      '1 '        2                142-    144    1638-   1647     537-    539     398-    404
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 1.460    0.120   10.000   20.000    1.700   -1.700   30.000   10.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37317      '1 '        2                145-    147    1648-   1657     540-    542     405-    411
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 2.300    0.120   10.000   20.000    1.700   -1.700   45.000    0.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37318      '1 '        2                148-    150    1658-   1667     543-    545     412-    418
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 6.900    0.120   10.000   20.000    1.700   -1.700  120.000   50.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37319      '1 '        2                151-    153    1668-   1677     546-    548     419-    425
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 6.900    0.120   10.000   20.000    1.700   -1.700  120.000    0.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37303      '1 '        2                154-    156    1678-   1687     549-    551     426-    432
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 6.150    0.120   10.000   20.000    5.000   -5.000   51.000   30.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37304      '1 '        2                157-    159    1688-   1697     552-    554     433-    439
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 3.200    0.120   10.000   20.000    5.000   -5.000   51.000   30.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
   37311      '1 '        2                160-    162    1698-   1707     555-    557     440-    446
  RF       AF      TLEAD    TLAG     R up    R down     Pmax     Pmin      EPF     Tpact
 2.720    0.120   10.000   20.000    5.000   -5.000   50.000    0.000    1.000    1.000
```

Figure B-2. Dynamic Data Documentation of the SMUD System AGC Model with the 22 Original Generating Units (cont.)

```
** AGC01 **     I C O N S      C O N S     S T A T E S     V A R S
                 223-265      1904-1921      602-608       523-536

     AGC FLAG  NTIE    NDM    ACE/ECONOMY
        1      12       1       0

   (---------------    AGC CONSTANTS - MAIN CONTROL   -------------------)
       BF       Kace      K1      lim       Tf       Ti      Tace     Tsum
   2000.000    1.000 1000.000   10.000    5.000   10.000   10.000   10.000

     (-------- TIE LINES --------)
     FROM BUS      TO BUS    CKTID
      30000        37005      '1 '
      30000        37005      '2 '
      30000        37010      '1 '
      30000        37010      '2 '
      30000        37010      '3 '
      30000        37010      '4 '
      30000        37012      '1 '
      30000        37012      '2 '
      30000        37013      '1 '
      30000        37016      '1 '
      30000        37016      '2 '
      30000        37021      '2 '

     MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
        30000      '1 '        2                263-    265    1912-   1921     606-    608     530-    536
      RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
     2.000    0.120   20.000    20.000 2000.000 -2000.00  205000. 1000.000    1.000    1.000
```

Figure B-2. Dynamic Data Documentation of the SMUD System AGC Model with the 22 Original Generating Units (cont.)

```
** PSHTNY **  BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S     V A R S      I C O N S
            37111 LAKE 1       69.000 1    1536-1595      508-516       288-298        57-60

    H0_t      rgate_t     Dturb_t    Trate_t    rpe_t      Tpe_t
    1.0000     0.0000     0.5000   150.0000     0.0500      1.0000

    Kigov_t   Kpgov_t     Kdgov_t    Tdgov_t
    0.2000     3.0000     0.0000     0.1000

    Kp_t      Tp_t        qnl_t      At_t
    1.0000     0.5000     0.0800     1.2000

    Gmax1_t   Gmin1_t     Gmax2_t    Gmin2_t
    1.0000     0.0000     1.0200     0.0000

    Vop_t     Vol_t       DB_spd1_t  DB_spd2_t
    2.0000    -2.0000    -0.0010     0.0010

    Gate1_t   Pg1_t       Gate2_t    Pg2_t      Gate3_t     Pg3_t
    0.0000     0.0000     0.4000     0.4000     0.6000      0.6000

    Gate4_t   Pg4_t       Gate5_t    Pg5_t
    0.8000     0.8000     1.0000     1.0000

    Dturb_p   Trate_p     Kp_p       Tp_p       qnl_p       At_p
    0.5000   300.0000    10.0000     0.1000     0.0800      1.2000

    Gmax1_p   GMin1_p     Vop_p      Vol_p      A0_p        B0_p       C0_p
    1.0000     0.0000     2.0000    -2.0000     1.1740    -0.6660     -0.3540

    Gate1_p   Pg1_p       Gate2_p    Pg2_p      Gate3_p     Pg3_p
    0.0000     0.0000     0.4000     0.4000     0.6000      0.6000

    Gate4_p   Pg4_p       Gate5_p    Pg5_p
    0.8000     0.8000     1.0000     1.0000

    Twtt1     Twtp1       Twpt1      Twpp1      Kd
    1.1700     0.0000     0.0000    -1.1700      2.0000

    ICON(M)   -  UNIT US  =       0  ICON(M+1)  ID =$$

    Turbine actived  =       1

    Pump    actived  =       1
```

Figure B-3. Dynamic Data Documentation of the Ternary Unit in Hydraulic Short Circuit Mode

```
** PSHTNY **  BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S     V A R S      I C O N S
            37122 LAKE 2       69.000 1    1596-1655      517-525       299-309        61-64

    H0_t      rgate_t     Dturb_t    Trate_t    rpe_t      Tpe_t
    1.0000     0.0000     0.5000   150.0000     0.0500      1.0000

    Kigov_t   Kpgov_t     Kdgov_t    Tdgov_t
    0.2000     3.0000     0.0000      0.1000

    Kp_t      Tp_t        qnl_t      At_t
    1.0000     0.5000     0.0800      1.2000

    Gmax1_t   Gmin1_t     Gmax2_t    Gmin2_t
    1.0000     0.0000     1.0200      0.0000

    Vop_t     Vol_t       DB_spd1_t  DB_spd2_t
    2.0000    -2.0000    -0.0010      0.0010

    Gate1_t   Pg1_t       Gate2_t    Pg2_t      Gate3_t     Pg3_t
    0.0000     0.0000     0.4000     0.4000     0.6000      0.6000

    Gate4_t   Pg4_t       Gate5_t    Pg5_t
    0.8000     0.8000     1.0000      1.0000

    Dturb_p   Trate_p     Kp_p       Tp_p       qnl_p       At_p
    0.5000   300.0000    10.0000     0.1000     0.0800      1.2000

    Gmax1_p   GMin1_p     Vop_p      Vol_p      A0_p        B0_p      C0_p
    1.0000     0.0000     2.0000    -2.0000     1.1740     -0.6660    -0.3540

    Gate1_p   Pg1_p       Gate2_p    Pg2_p      Gate3_p     Pg3_p
    0.0000     0.0000     0.4000     0.4000     0.6000      0.6000

    Gate4_p   Pg4_p       Gate5_p    Pg5_p
    0.8000     0.8000     1.0000      1.0000

    Twtt1     Twtp1       Twpt1      Twpp1      Kd
    1.1700     0.0000     0.0000    -1.1700      2.0000

    ICON(M)   -  UNIT US  =       0  ICON(M+1)  ID =$$

    Turbine active  =       1

    Pump    active  =       1
```

Figure B-3. Dynamic Data Documentation of the Ternary Unit in Hydraulic Short Circuit Mode (cont.)

```
** AGC01 **     I C O N S      C O N S     S T A T E S     V A R S
                 111-222      1656-1903      526-601       348-522

   AGC FLAG  NTIE    NDM    ACE/ECONOMY
       1      12      24       0

  (---------------    AGC CONSTANTS - MAIN CONTROL   -------------------)
     BF      Kace      K1      lim       Tf       Ti      Tace     Tsum
   81.000    1.000 1000.000   10.000    5.000   10.000   10.000   10.000

   (-------- TIE LINES --------)
   FROM BUS      TO BUS    CKTID
    37005        30000      '1 '
    37005        30000      '2 '
    37010        30000      '1 '
    37010        30000      '2 '
    37010        30000      '3 '
    37010        30000      '4 '
    37012        30000      '1 '
    37012        30000      '2 '
    37013        30000      '1 '
    37016        30000      '1 '
    37016        30000      '2 '
    37021        30000      '2 '

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37310      '1 '         2               151-    153    1664-  1673     530-    532     355-    361
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   2.700    0.120   10.000   20.000    5.000   -5.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37312      '1 '         2               154-    156    1674-  1683     533-    535     362-    368
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   2.700    0.120   10.000   20.000    5.000   -5.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37313      '1 '         2               157-    159    1684-  1693     536-    538     369-    375
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   3.500    0.120   10.000   20.000   10.000  -10.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37315      '1 '         2               160-    162    1694-  1703     539-    541     376-    382
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   2.950    0.120   10.000   20.000    5.000   -5.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37315      '2 '         2               163-    165    1704-  1713     542-    544     383-    389
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   1.290    0.120   10.000   20.000    5.000   -5.000   15.000    0.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37316      '1 '         2               166-    168    1714-  1723     545-    547     390-    396
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   2.950    0.120   10.000   20.000    5.000   -5.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37320      '1 '         2               169-    171    1724-  1733     548-    550     397-    403
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   1.327    0.120   10.000   20.000    5.000   -5.000   25.000    0.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37321      '1 '         2               172-    174    1734-  1743     551-    553     404-    410
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
  11.500    0.120   10.000   20.000    5.000   -5.000  200.000   50.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37322      '1 '         2               175-    177    1744-  1753     554-    556     411-    417
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
  11.500    0.120   10.000   20.000    5.000   -5.000  200.000   50.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37323      '1 '         2               178-    180    1754-  1763     557-    559     418-    424
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
  11.200    0.120   10.000   20.000   10.000  -10.000  200.000   50.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37301      '1 '         2               181-    183    1764-  1773     560-    562     425-    431
    RF       AF      TLEAD     TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   3.700    0.120   10.000   20.000    1.700   -1.700   70.000   10.000    1.000    1.000
```

Figure B-4. Dynamic Data Documentation of the SMUD System AGC Model

with the 22 Original Generating Units and Two Ternary Pumps

```
 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37302      '1 '        2                184-    186    1774-  1783     563-    565     432-    438
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 3.700    0.120   10.000   20.000    1.700   -1.700   70.000   10.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37305      '1 '        2                187-    189    1784-  1793     566-    568     439-    445
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 3.700    0.120   10.000   20.000    1.700   -1.700   70.000   10.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37306      '1 '        2                190-    192    1794-  1803     569-    571     446-    452
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 3.800    0.120   10.000   20.000    1.700   -1.700   70.000   10.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37309      '1 '        2                193-    195    1804-  1813     572-    574     453-    459
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 4.050    0.120   10.000   20.000   10.000  -10.000   75.000    0.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37314      '1 '        2                196-    198    1814-  1823     575-    577     460-    466
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 1.460    0.120   10.000   20.000    1.700   -1.700   30.000   10.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37317      '1 '        2                199-    201    1824-  1833     578-    580     467-    473
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 2.300    0.120   10.000   20.000    1.700   -1.700   45.000    0.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37318      '1 '        2                202-    204    1834-  1843     581-    583     474-    480
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 6.900    0.120   10.000   20.000    1.700   -1.700  120.000   50.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37319      '1 '        2                205-    207    1844-  1853     584-    586     481-    487
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 6.900    0.120   10.000   20.000    1.700   -1.700  120.000    0.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37303      '1 '        2                208-    210    1854-  1863     587-    589     488-    494
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 6.150    0.120   10.000   20.000    5.000   -5.000   51.000   30.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37304      '1 '        2                211-    213    1864-  1873     590-    592     495-    501
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 3.200    0.120   10.000   20.000    5.000   -5.000   51.000   30.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37311      '1 '        2                214-    216    1874-  1883     593-    595     502-    508
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
 2.720    0.120   10.000   20.000    5.000   -5.000   50.000    0.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37111      '1 '        2                217-    219    1884-  1893     596-    598     509-    515
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
10.000    0.120   10.000   20.000    5.000   -5.000  150.000    0.000    1.000    1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37122      '1 '        2                220-    222    1894-  1903     599-    601     516-    522
  RF       AF      TLEAD     TLAG      R up    R down    Pmax      Pmin      EPF     Tpact
10.000    0.120   10.000   20.000    5.000   -5.000  150.000    0.000    1.000    1.000
```

Figure B-4. Dynamic Data Documentation of the SMUD System AGC Model with the 22 Original Generating Units and Two Ternary Pumps (cont.)

```
                         ** AGC01 **     I C O N S      C O N S     S T A T E S     V A R S
                                   223-265      1904-1921      602-608       523-536

   AGC FLAG  NTIE    NDM    ACE/ECONOMY
       1      12       1       0

 (---------------    AGC CONSTANTS - MAIN CONTROL   -------------------)
     BF       Kace      K1      lim       Tf       Ti      Tace     Tsum
 2000.000    1.000 1000.000   10.000    5.000   10.000   10.000   10.000

   (-------- TIE LINES --------)
   FROM BUS      TO BUS    CKTID
    30000        37005      '1 '
    30000        37005      '2 '
    30000        37010      '1 '
    30000        37010      '2 '
    30000        37010      '3 '
    30000        37010      '4 '
    30000        37012      '1 '
    30000        37012      '2 '
    30000        37013      '1 '
    30000        37016      '1 '
    30000        37016      '2 '
    30000        37021      '2 '

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      30000      '1 '         2                263-    265    1912-   1921     606-    608     530-    536
    RF       AF      TLEAD     TLAG     R up    R down    Pmax      Pmin      EPF     Tpact
   2.000    0.120   20.000   20.000 2000.000 -2000.00  205000. 1000.000    1.000    1.000
```

Figure B-4. Dynamic Data Documentation of the SMUD System AGC Model with the 22 Original Generating Units and Two Ternary Pumps (cont.)

```
             ** PSHPMP **  BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S     V A R S      I C O N S
          37111 LAKE 1              69.000 1     331-390       141-159         1-22          1-8

  TIqCmd     TIpCmd     VLVPL1      VLVPL2    GLVPL
  0.0200     0.0200     0.4000      0.1000    1.0000

  VHVRCR    CURHVRCR    RIp_LVPL    T_LVPL
  1.1000     2.0000    15.0000      0.0200

  Khv       Iqrmax      Iqrmin
  0.7000     2.0000     -2.0000

  H         R          Tv         TE         Tp         Tbf        Tn
  5.5800    0.0500     0.0200     0.0200     0.0200     0.0200     1.0000

  Tnp       Tff        Tr         Tpo        Kpv        Kiv        rr
  1.0000    0.0200     0.5000     0.0200     1.0000     1.0000     0.2500

  Kp2       Ki2        Kpsp       Kisp       SPmax      SPMin      Pmax       PMin
  1.0000    1.0000     0.0000     0.5000     0.0500    -0.0500     0.0000    -1.0000

  IPmax     IPMin      dPmax      dPMin      Eqmax      Eqmin      fdbd
  1.2000   -1.2000     0.0100    -0.0100     2.5000     0.7000     0.0050

  H0        Dturb      Trate      Kg1        Tg1        Kp1        Tp1        qnl
  1.0000    0.5000     1.0000     1.0000     0.5000    10.0000     0.1000    -0.0800

  Gmax1     GMin1      Vop1       Vol1        A0         B0         C0
  1.0000    0.0000     2.0000    -2.0000     1.1740    -0.0666    -0.3540

  Tw        Tw1        Tw2       Tw3
 -0.8300    0.0000     0.0000     0.0000

  ICON(M)    -  REMOTE BUS  =   37111

  ICON(M+2) -  UNIT 1 BUS  =       0  ICON(M+3)  ID =' 1'

  ICON(M+4) -  UNIT 2 BUS  =       0  ICON(M+5)  ID =' 1'

  ICON(M+6) -  UNIT 3 BUS  =       0  ICON(M+7)  ID =' 1'
```

Figure B-5. Dynamic Data Documentation of the AS Pump Model

```
** PSHPMP **  BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S     V A R S      I C O N S
             37122 LAKE 2       69.000 1     391-450       160-178        23-44          9-16

     TIqCmd     TIpCmd     VLVPL1      VLVPL2    GLVPL
     0.0200     0.0200     0.4000      0.1000    1.0000

     VHVRCR    CURHVRCR    RIp_LVPL    T_LVPL
     1.1000     2.0000    15.0000      0.0200

     Khv       Iqrmax      Iqrmin
     0.7000     2.0000     -2.0000

     H         R          Tv         TE         Tp         Tbf        Tn
     5.5800    0.0500     0.0200     0.0200     0.0200     0.0200     1.0000

     Tnp       Tff        Tr         Tpo        Kpv        Kiv        rr
     1.0000    0.0200     0.5000     0.0200     1.0000     1.0000     0.2500

     Kp2       Ki2        Kpsp       Kisp       SPmax      SPMin      Pmax       PMin
     1.0000    1.0000     0.0000     0.5000     0.0500    -0.0500     0.0000    -1.0000

     IPmax     IPMin      dPmax      dPMin      Eqmax      Eqmin      fdbd
     1.2000   -1.2000     0.0100    -0.0100     2.5000     0.7000     0.0050

     H0        Dturb      Trate      Kg1        Tg1        Kp1        Tp1        qnl
     1.0000    0.5000     1.0000     1.0000     0.5000    10.0000     0.1000    -0.0800

     Gmax1     GMin1      Vop1       Vol1        A0         B0         C0
     1.0000    0.0000     2.0000    -2.0000     1.1740    -0.0666    -0.3540

     Tw        Tw1        Tw2       Tw3
    -0.8300    0.0000     0.0000     0.0000

     ICON(M)   -  REMOTE BUS  =   37122

     ICON(M+2) -  UNIT 1 BUS  =       0  ICON(M+3)  ID =' 1'

     ICON(M+4) -  UNIT 2 BUS  =       0  ICON(M+5)  ID =' 1'

     ICON(M+6) -  UNIT 3 BUS  =       0  ICON(M+7)  ID =' 1'
```

Figure B-5. Dynamic Data Documentation of the AS Pump Model (cont.)

```
** AGC01 **     I C O N S      C O N S     S T A T E S     V A R S
                  73-184      1600-1847      526-601       330-504

   AGC FLAG  NTIE    NDM    ACE/ECONOMY
       1      12      24        0

  (---------------    AGC CONSTANTS - MAIN CONTROL   -------------------)
     BF       Kace     K1       lim       Tf        Ti       Tace     Tsum
   81.000    1.000 1000.000   10.000    5.000   10.000   10.000   10.000

   (-------- TIE LINES --------)
   FROM BUS      TO BUS    CKTID
    37005        30000      '1 '
    37005        30000      '2 '
    37010        30000      '1 '
    37010        30000      '2 '
    37010        30000      '3 '
    37010        30000      '4 '
    37012        30000      '1 '
    37012        30000      '2 '
    37013        30000      '1 '
    37016        30000      '1 '
    37016        30000      '2 '
    37021        30000      '2 '

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37310      '1 '         2                113-    115    1608-  1617      530-    532     337-    343
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
   2.700    0.120   10.000   20.000    5.000    -5.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37312      '1 '         2                116-    118    1618-  1627      533-    535     344-    350
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
   2.700    0.120   10.000   20.000    5.000    -5.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37313      '1 '         2                119-    121    1628-  1637      536-    538     351-    357
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
   3.500    0.120   10.000   20.000   10.000   -10.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37315      '1 '         2                122-    124    1638-  1647      539-    541     358-    364
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
   2.950    0.120   10.000   20.000    5.000    -5.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37315      '2 '         2                125-    127    1648-  1657      542-    544     365-    371
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
   1.290    0.120   10.000   20.000    5.000    -5.000   15.000    0.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37316      '1 '         2                128-    130    1658-  1667      545-    547     372-    378
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
   2.950    0.120   10.000   20.000    5.000    -5.000   50.000   10.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37320      '1 '         2                131-    133    1668-  1677      548-    550     379-    385
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
   1.327    0.120   10.000   20.000    5.000    -5.000   25.000    0.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37321      '1 '         2                134-    136    1678-  1687      551-    553     386-    392
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
  11.500    0.120   10.000   20.000    5.000    -5.000  200.000   50.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37322      '1 '         2                137-    139    1688-  1697      554-    556     393-    399
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
  11.500    0.120   10.000   20.000    5.000    -5.000  200.000   50.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37323      '1 '         2                140-    142    1698-  1707      557-    559     400-    406
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
  11.200    0.120   10.000   20.000   10.000   -10.000  200.000   50.000    1.000    1.000

   MACHINE BUS    ID    CONTROL SWITCH     (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      37301      '1 '         2                143-    145    1708-  1717      560-    562     407-    413
    RF       AF      TLEAD    TLAG      R up    R down    Pmax     Pmin      EPF     Tpact
   3.700    0.120   10.000   20.000    1.700    -1.700   70.000   10.000    1.000    1.000
```

Figure B-6. Dynamic Data Documentation of the SMUD System AGC Model with the 22 Original Generating Units and Two AS Pumps

```
 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37302      '1 '        2                146-    148    1718-   1727     563-    565     414-    420
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 3.700    0.120   10.000   20.000   1.700   -1.700   70.000   10.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37305      '1 '        2                149-    151    1728-   1737     566-    568     421-    427
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 3.700    0.120   10.000   20.000   1.700   -1.700   70.000   10.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37306      '1 '        2                152-    154    1738-   1747     569-    571     428-    434
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 3.800    0.120   10.000   20.000   1.700   -1.700   70.000   10.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37309      '1 '        2                155-    157    1748-   1757     572-    574     435-    441
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 4.050    0.120   10.000   20.000  10.000  -10.000   75.000    0.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37314      '1 '        2                158-    160    1758-   1767     575-    577     442-    448
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 1.460    0.120   10.000   20.000   1.700   -1.700   30.000   10.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37317      '1 '        2                161-    163    1768-   1777     578-    580     449-    455
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 2.300    0.120   10.000   20.000   1.700   -1.700   45.000    0.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37318      '1 '        2                164-    166    1778-   1787     581-    583     456-    462
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 6.900    0.120   10.000   20.000   1.700   -1.700  120.000   50.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37319      '1 '        2                167-    169    1788-   1797     584-    586     463-    469
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 6.900    0.120   10.000   20.000   1.700   -1.700  120.000    0.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37303      '1 '        2                170-    172    1798-   1807     587-    589     470-    476
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 6.150    0.120   10.000   20.000   5.000   -5.000   51.000   30.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37304      '1 '        2                173-    175    1808-   1817     590-    592     477-    483
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 3.200    0.120   10.000   20.000   5.000   -5.000   51.000   30.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37311      '1 '        2                176-    178    1818-   1827     593-    595     484-    490
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
 2.720    0.120   10.000   20.000   5.000   -5.000   50.000    0.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37111      '1 '        1                179-    181    1828-   1837     596-    598     491-    497
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
10.000    0.120   10.000   20.000   1.700   -1.700  150.000    0.000    1.000     1.000

 MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
    37122      '1 '        1                182-    184    1838-   1847     599-    601     498-    504
  RF       AF      TLEAD    TLAG     R up    R down    Pmax      Pmin       EPF      Tpact
10.000    0.120   10.000   20.000   1.700   -1.700  150.000    0.000    1.000     1.000
```

Figure B-6. Dynamic Data Documentation of the SMUD System AGC Model with 22 the Original Generating Units and Two AS Pumps (cont.)

```
** AGC01 **     I C O N S      C O N S     S T A T E S     V A R S
                 185-227      1848-1865      602-608       505-518

   AGC FLAG  NTIE    NDM    ACE/ECONOMY
       1      12       1       0

 (---------------    AGC CONSTANTS - MAIN CONTROL   -------------------)
     BF       Kace     K1      lim       Tf       Ti      Tace     Tsum
 2000.000    1.000 1000.000   10.000    5.000   10.000   10.000   10.000


   (-------- TIE LINES --------)
   FROM BUS      TO BUS    CKTID
    30000        37005      '1 '
    30000        37005      '2 '
    30000        37010      '1 '
    30000        37010      '2 '
    30000        37010      '3 '
    30000        37010      '4 '
    30000        37012      '1 '
    30000        37012      '2 '
    30000        37013      '1 '
    30000        37016      '1 '
    30000        37016      '2 '
    30000        37021      '2 '

   MACHINE BUS    ID    CONTROL SWITCH    (--- ICONS ---) (---  CONS ---) (--  STATES --) (---  VARS ---)
      30000      '1 '         2                225-    227    1856-   1865     606-    608     512-    518
    RF       AF      TLEAD    TLAG     R up    R down    Pmax     Pmin      EPF     Tpact
   2.000    0.120   20.000   20.000 2000.000 -2000.00 205000.000 1000.000   1.000    1.000
```

Figure B-6. Dynamic Data Documentation of the SMUD System AGC Model with the 22 Original Generating Units and Two AS Pumps (cont.)

This page intentionally left blank.

Decision and Information Sciences
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 221
Argonne, IL 60439-4844

www.anl.gov

U.S. DEPARTMENT OF
ENERGY