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SUGGESTED PERFORMANCE SPECIFICATIONS OF STANDARD
MODULAR CONTROLS FOR THE AUTOMATION OF SMALL
HYDRO ELECTRIC FACILITIES

By
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Beckwith Electric Company, Inc.
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U. S. DEPARTMENT OF ENERGY

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FOR THE AUTOMATION OF SMALL HYDRO ELECTRIC FACILITIES**

**PREPARED UNDER CONTRACT NO. DE-AC07-76ID01570 WITH THE UNITED
STATES GOVERNMENT REPRESENTED BY THE IDAHO OPERATIONS OFFICE OF
THE DEPARTMENT OF ENERGY**

JUNE, 1980

PRINCIPAL AUTHOR

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TABLE OF CONTENTS

I. INTRODUCTION

II. GENERAL SPECIFICATIONS

1.0 Scope

- 1.1 Overall Requirements
- 1.2 Plant Data

2.0 Plant Interface

- 2.1 Water Regulating Valve Control
- 2.2 Rotating Blade Control
- 2.3 Field Control
- 2.4 Mechanical Mounting

3.0 Interconnection to Distribution Line

- 3.1 Fault Clearing
- 3.2 Voltage Excursion
- 3.3 Frequency Excursion
- 3.4 Wave Shape Distortion
- 3.5 Connection
- 3.6 Voltage Regulation
- 3.7 Voltage Balance
- 3.8 Fault Conditions

4.0 Requirements for DPU Hardware

- 4.1 Mechanical Mounting
- 4.2 Digital Processing Unit (DPU)
- 4.3 Display and Control Panel
- 4.4. Permanent Data Storage Device (PDSD)
- 4.5 Power Connection to DPU
- 4.6 Real Time Clock

5.0 Maintenance Unit

- 5.1 Mounting
- 5.2 CRT
- 5.3 Connectors
- 5.4 Capability

6.0 DPU Programs

- 6.1 Programming Language
- 6.2 Program Performance Specification
- 6.3 Program Acceptance Test Plan
- 6.4 Program Requirements

- 7.0 Plant Peripheral Devices
 - 7.1 Common Requirements
 - 7.2 Type A
 - 7.3 Type B
 - 7.4 Type C Contact Monitor
 - 7.5 Type D Transducer
 - 7.6 Potential Transducer
 - 7.7 Connections for RPD
- 8.0 Communications Interface Specifications
 - 8.1 Fiber Optic Interface
 - 8.2 Plant I/O Modules
 - 8.3 Communications and Control
- 9.0 Automatic Synchronizer
 - 9.1 Control Functions
 - 9.2 Features
 - 9.3 Environmental
 - 9.4 Reliability & Maintainability
 - 9.5 Electrical
 - 9.6 Settings
- 10.0 Documentation
 - 10.1 Standard Drawing Sizes
 - 10.2 Schematics
 - 10.3 External Connection Diagrams
 - 10.4 Mechanical Drawings
 - 10.5 Computer Program Flow Diagrams
 - 10.6 Block Diagrams
 - 10.7 Parts Lists
 - 10.8 Maintenance Manual
 - 10.9 Spares
 - 10.10 Descriptive Material
- 11.0 Drawing Submittal
 - 11.1 Schematics
 - 11.2 Program
 - 11.3 Final Data

III. APPENDIX

- A. I. Introduction
- II. Plant Interface
- III. Connection to Distribution Line
- IV. Requirements for DPU Hardware
- V. Maintenance Unit
- VI. DPU Programs
- VII. Plant Peripheral Devices
- VIII. Fiber Optics as the Interconnection Media
- IX. Automatic Synchronizing

B. Scope of Work

C. Calculations of Circuit Breaker Closing Criteria for
Synchronizing a Generator

D. Comparison of Papers

IV. ABBREVIATIONS USED

V. GLOSSARY

VI. REFERENCES

I. INTRODUCTION

THE HYDRO POTENTIAL IN THE UNITED STATES

The Corps of Engineers in a report (Ref. 1) has stated that in 1979, hydropower provided about 13% of the nation's total electrical power with installed capacity of about 64 Gigawatts and an average annual energy generation of some 0.96 Quads.

This same report shows a total undeveloped hydro potential of more than 512 Gigawatts which is somewhat greater than the nameplate capacity of generation of all kinds in 1980. The report estimates an undeveloped annual energy availability of over 4.7 Quads. Of this potential, the report lists 94 Gigawatts at existing dams and waterways having no present generation equipment but capable of producing 0.76 Quads of energy per year.

This same report implies a total electrical usage in 1979 of 7.4 Quads. Note that the input required by the fossil or nuclear portion of the total will be some 3 times the output.

An extrapolation of an Exxon report (Ref. 2) shows an energy input to the electric utility industry of 24 Quads in 1980 and projects a need for 36 Quads in the year 2000. This is an increase of 50% which, if added to the Corps of Engineers figure of 7.4 Quads in 1979, yields approximately 11.1 Quads of electrical output in 2000 or an increase of 3.7 Quads per year over the 21 year period.

It is interesting to note that if only .79% of the potential identified by the Corps of Engineers were developed, it would meet all of the need predicted by Exxon through the year 2000.

Most all of the large hydro potential has been developed. In many ways there are advantages, however, to the application of many small units. The problems of connection of a small unit to the electrical network are minimal and the disturbances created when the small unit trips are also minimal.

The problems and costs of control of a number of small units may, on the other hand, be great, possibly to the extent of making small hydro development uneconomical. This report is dedicated to solving these problems by means of low cost, local automatic control.

EXECUTIVE SUMMARY

A typical hydro installation has been defined for which specifications for automation have been prepared. It is believed that the modular form of the second portion of this document will permit editing into a particular specification for any plant in existence or planned for the future.

A number of key choices have been made in the interest of applying advanced technology to solve the important problems of high cost of software, transient protection, and reliability.

Use of Pascal as the standard computer language.

Use of a standard 19 inch mounting for control; NEMA enclosures for peripheral devices.

Use of fiber optic cables for all data paths.

Use of distributed batteries charged by a common 120 V ac supply.

Use of fail safe system philosophy where no single device failure can cause damage but will result in a safe machine shut down.

THE PROBLEM TO BE SOLVED

Small scale hydro, in order to be both economically and environmentally feasible, requires the development of new technologies with new approaches that solve problems which are peculiar to small scale hydro plants. This report focuses, in part, on one of the economic problems associated with small hydro. Namely, what is the best and most practical manner of completely automating small hydro plants in order to lessen the number of man hours required to operate the plant on a day to day basis?

A typical small hydro installation has been defined for which model automation specifications have been prepared in modular form in order to permit incorporation into specifications which vary from the standard model. This will facilitate, as nearly as possible, the widest use and adaptation of these specifications.

AUTHORITY

The engineering services were authorized under an agreement dated September 17th, 1979 by and between Beckwith Electric Company, Inc., Largo, Florida and EG&G, Idaho, Inc., Idaho Falls, Idaho representing the Idaho Operations Office of the Department of Energy.

SCOPE

The specific scope of engineering services is outlined in Appendix A of the aforementioned agreement, a copy of which is included in Appendix B of this report. Generally, the services comprise appraisals and definitions of performance specifications to automate the operation of small hydro plants ranging in size from fifty kilowatts to fifteen megawatts (upper limit now 25 MW).

ACKNOWLEDGEMENTS

Grateful acknowledgement is made of the excellent cooperation and assistance provided by the personnel of the Idaho Operations Office, EG&G Idaho, Inc., and the U.S. Department of Energy.

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Dr. William A. Lewis, Consulting Electrical Engineer, Sunnyvale, California, (408)732-9077.

T. R. Livermore, Consultant, Microcomputer Systems, Systems Design Concepts, Inc., Clearwater, Florida, (813)446-3041.

E. B. Scruggs, Registered Professional Engineer, Phoenix, Arizona, (602)959-7891.

PURPOSE OF SPECIFICATIONS

These specifications are made available by the Department of Energy for the voluntary use by any person, corporation or governmental body in the writing of purchase specifications for the automatic control of small hydro generating stations.

It is believed that the use of these specifications will permit competition amongst capable vendors and, at the same time, assure proper and reliable operation of both the hardware and software purchased.

The specifications are detailed to a degree which should assure the interchangeability of hardware and software from various suppliers. This also increases the likelihood that spare parts and service will be available for many years.

The specifications are written in modules, each of which can be

included or excluded for ease of editing to match a particular application. Brief but detailed instructions are included for such editing.

An extensive appendix gives the alternatives which were considered and reasons for the various choices specified.

BENEFITS EXPECTED FROM STANDARDIZATION

Standardization will minimize spare parts required to service a number of hydro plants in spite of differences between the plants and in spite of the source of the microcomputer or peripheral devices. The manufacturer will be able to use standard cards already available or likely to be available in the future.

Standardization will maximize the ease of obtaining spare cards and parts for at least 25 years in spite of the anticipated explosive technological growth of the computer industry.

Standardization will maximize the ease of adding features or changing the automation procedure using future hardware cards while, at the same time, discarding a minimum of original equipment.

Standardization will reduce the cost of original programming, changing the program and proving the program on the actual hydro generator. Present software costs tend to run as high as 10 times the hardware cost. A 10:1 reduction in software cost is a reasonable

goal for future programming efforts.

NOTE: Wherever a portion of this specification is enclosed in brackets, [], the portion may be omitted, changed to suit the application, or one of two or more alternatives within the bracket may be chosen. The brackets must be removed before the specification is issued.

Material inclosed in { } are explanatory for use in editing the specifications. This material and brackets must be removed before issuance of a purchase specification.

II. GENERAL SPECIFICATIONS

1.0 SCOPE

These specifications describe equipment to be furnished for the automatic operation of []. This section describes the overall approach and design philosophies which shall be followed. Overall plant parameters are contained in this section. Additional sections specify each system component in greater detail.

1.1 OVERALL REQUIREMENTS

1.1.1 The Digital Processing Unit (DPU) shall be a microprocessor based computer operating in a fail safe mode. Failure of the DPU, any of the data links to the hydro machine, or any of the peripheral devices shall result in safe shut down. The DPU is specified in detail in Section 4.

1.1.2 All data links from the DPU rack or cabinet to the outside world shall be by fiber optic cables.

1.1.3 The DPU shall be powered by self contained batteries capable of at least 48 hours operation without recharging.

1.1.4 All external interface devices and transducers shall either be powered by self contained batteries capable of at least 48 hours operation without recharging or from the electrical input being

measured where possible. Each of these devices shall be mounted as close to the point being measured or controlled as practical.

1.1.5 An isolated 120 V AC source shall be provided to power the DPU and associated peripheral devices. The isolated source shall have passed through a voltage regulating transformer.

1.1.6 Provision shall be made to permit energizing the source with a portable engine generator whose frequency may vary from 50 to 70 Hz.

1.1.7 The interface devices at the synchronizing circuit breaker and at the main water shut off gate shall be applied so as to trip and close respectively should a repetitive signal not be received from the DPU for a period of time. Thus a broken fiber optic cable, failed DPU or light sender shall cause a plant shutdown.

1.1.8 An electromechanical hydro plant simulator shall be made available to permit exercising the DPU together with all transducers, interface devices and interconnecting optical cables in order to thoroughly test the automation equipment either in the factory prior to shipment or in the field prior to actual control of the machine.

Alternatively the supplier shall propose a method to thoroughly demonstrate proper system operation of the DPU with all peripheral

devices connected and completed program in use before attempting automatic operation of the hydro generator.

1.1.9 Programming shall be done in Pascal in compliance with ISO proposed standard 7185 submitted to ANSI on May 19, 1980 or the revised version accepted by ANSI.

1.1.10 The equipment shall be designed for an overall mean life between failure of 10,000 hours per MIL 461.

1.1.11 The equipment shall be designed and spare parts provided to permit an average repair time of two hours.

1.1.12 Documentation supporting 1.1.10 and 1.1.11 shall be provided with the bid.

1.1.13 Warning instructions shall be included with the equipment with the following priorities:

- (a) Protection of personnel from harm.
- (b) Protection of plant from damage.
- (c) Protection of automation equipment from damage.

These warning instructions shall be written in the following language or languages: []. Use of universally understood diagrams or sketches shall be used wherever possible.

1.2 PLANT DATA

1.2.1 The kilowatt loading on the plant shall be determined by:

[Available water:

Setpoint contained in computer program:

Local manually adjustable setpoint:

Remotely adjustable setpoint:

A river flow computer (see Appendix Page 5):

Customer load]

1.2.2 The kilovar loading shall be determined by

[Not controlled:

Setpoint contained in computer program:

Local manually adjustable setpoint:

Remotely adjustable setpoint]

1.2.3 The unit shall be started and stopped by:

[A trained operator at the plant:

An untrained operator capable of only pushing a start button:

A remote command:

Time of day:

Forebay water level:

Afterbay water level:

A function of two water levels:

Other]

1.2.4 The machine [is: is not] equipped with a variable pitch propeller.

1.2.5 The field shall be controlled so as to maintain:

[Line voltage:

Power factor]

1.2.7 There [is: is not] an electrically controlled gate which must be closed on failure of the water control valve, such as wicket gate shear pin failure.

{NOTE: These standards contemplate an installation with some or all of the components shown in Diagram 1.2.6.

It is contemplated that each block of Diagram 1.2.6 may be located physically separate from another. Horizontal lines within a block imply 19" rack mounted equipment. Other boxes imply a NEMA housing. Where plant geometry permits, blocks shown separately in Diagram 1.2.6 may be combined in one housing.

Note that no generator step up transformer is shown. The breaker may be on either side of this transformer, but generally the high side. If there is a breaker on either side of the transformer, one will be designated the synchronizing breaker. For the purpose of the typical scheme, it is therefore adequate to show one breaker as in Diagram 1.2.6. A block diagram should be prepared along the scheme illustrated by diagram 1.2.6, but specifically altered to match the installation for which the edited specification is to apply.}

1.2.8 A description of the blocks is as follows (see Section 7.0 for description of peripheral devices A through F).

1.2.8.1 Automatic Synchronizer: This shall close the breaker contacts at the next available proper phase condition, taking into account the expected breaker closing time. Frequency difference, voltage difference and line voltage shall be independently checked by the automatic synchronizer.

1.2.8.2 A Type A device shall close a redundant breaker close contact in series with the Automatic Synchronizer contact. This A device (See Section 7) contact shall be closed by the DPU within phase angle calculated to be safe. See Section 9.2.5.

1.2.8.3 A Type D peripheral device shall telemeter to the DPU, via fiber optic cables, the following in addition to breaker position:

With Breaker Open:

Line Voltage

[Line Voltage Balance]

[Total Harmonic Distortion]

[Flicker]

Scaler voltage difference across breaker

Shaft RPM

With Breaker Closed

Line Voltage

[Line Voltage Balance]

[Total Harmonic Distortion]

[Flicker]

Watts.

VARs

Frequency deviation from 60 Hz (with polarity)

1.2.8.4 Field Control: A Type A peripheral device shall raise or lower the field with the following expected result:

With Breaker Open: Changes the scalar voltage difference across the breaker.

[With Breaker closed into a nearby substation: changes VARs] or

[With Breaker closed into a distribution circuit: changes voltage.]

1.2.8.5 [Rotating Blade Angle Control: A Type A peripheral device shall set the desired blade angle which in turn determines machine efficiency.]

{Generally controlled by table look up for Watts load, forebay and afterbay water levels; in which case feedback is blade angle via a Type B peripheral device to the computer. In a more advanced form, feedback may be via calculation of machine efficiency.

NOTE: Not all machines have variable pitch propellers.)

1.2.8.6 Water Flow: A Type A peripheral device shall set the desired gate position in response to DPU commands. Feedback to the computer shall be one of the following:

With Breaker Open: Control of generator frequency (Δf across breaker).

With Breaker Closed: Control of kW machine output.

1.2.8.7 [Water Shut Off Valve]

{May be electrically closed via a Type A peripheral device to stop water flow if pin shears in water flow control valve or if there is another reason for a secondary water flow control.

NOTE: Not all machines have this valve.}

1.2.8.8 Protective Relays

{These are not covered in this document; however the following is assumed:

The Protective Relay will trip the circuit breaker directly. The circuit breaker status contact will initiate DPU control action via a Type C device as a result of the breaker tripping.

In an advanced type of Protective Relay, prefault data may be transmitted to the DPU via a fiber optic cable for data logging.}

1.2.8.9 Minimal Display: This is described in detail in Section 4.

1.2.8.10 Mode Control: This is described in detail in Section 4.

1.2.8.11 [Forebay/Afterbay Water Levels: Shall be telemetered to the DPU via fiber optic cables. Type B or F peripheral device shall be located at each water level measuring position.]

{Included only when these levels are required for control.}

1.2.8.12 Contact Monitor: Each Type C device shall monitor and report the status of up to 8 contacts via a fiber optic cable. These devices shall be mounted as required so that no wire runs from contact to device exceed 10 meters.

1.2.8.13 [SPILLWAY GATE CONTROL

This shall be controlled by an independent system operating from an independent high head water level detector normally to spill excess water when not used for generation and also to safely spill water in the event of failure of the automation system.]

{Not all dams will have this requirement.}

2.0 PLANT INTERFACE (Ref. 3)

{In order to automatically control a hydro generator an interface must be defined between the machine and the control. Both sides of the interface must be specified; this section specifies the machine side.}

2.1 WATER REGULATING VALVE CONTROL

Valve position shall be sensed with an accuracy of 1% of full travel.

Reception of an open or close code shall:

- a) cause an incremental rotation of a stepping motor, or
- b) shall position a DC motor capable of holding its position by friction, or
- c) alter the position of a piston in a hydraulic cylinder, or
- d) an equivalent means.

{It is anticipated that the position of the main water valve will be telemetered back to the DPU only if required for control or safe operation.}

The device representing the set point position for the valve shall move in the open direction upon receipt of an x contact closure and in the close direction upon receipt of a y contact closure from the

valve control unit. The contact requirements shall be no more than 150 V ac or V dc at one amp inductive.

The rate of rotation of the valve with either contact continuously closed shall be no faster than is safe for the machine. This rate shall be made available for the specification of the computer program.

Limit switches shall open up the input control circuits to prevent damage.

The valve shall safely close upon failure of the DPU, or the fiber optic cable to the valve control, or loss of power at the valve control

2.2 [ROTATING BLADE CONTROL

The requirements shall be identical to 2.1 except failures shall result in the blade remaining at its last controlled angle.]

2.3 FIELD CONTROL

Provision shall be made to hold the field [voltage: current] set point. The means for doing this shall be such that the set point may be increased by closing an x contact or decreased by closing a y contact from the controller. The contact requirements shall be no more than 150 V ac or V dc at one amp inductive. The set point shall hold its position indefinitely with no x or y contact closures.

Alternatively, a Type E analog output device may be used to generate a setpoint input to the field control.

2.4 MECHANICAL MOUNTING

Provision shall be made for mounting a NEMA box as required for each peripheral device.

3.0 INTERCONNECTION TO DISTRIBUTION LINE

{NOTE: This entire section may be omitted if the generator is tied directly to a substation in such a way that there is no possibility of an isolated connection from this generator to loads other than plant loads at the generator site.}

3.1 Fault Clearing

Single line to ground, phase to phase and three phase faults must be detected and the small generator disconnected within [0.2] seconds.

3.2 Voltage Excursion

If the phase to phase voltage goes outside limits of $\pm[0.1]$ per unit for more than [one] second the small generator shall immediately be disconnected. The time shall decrease linearly to a value of [0.1] seconds for overvoltages between 0.1 and 0.2 per unit and remain less than [0.1] seconds for overvoltages more than 1.2 p.u.

3.3 Frequency Excursion

If the frequency goes outside the limit of $60\pm[0.5]$ Hz for more than one second, the small generator shall immediately be disconnected.

3.4 [Wave Shape Distortion

The voltage waveshape shall contain no more than $\pm[10\%]$ total harmonic distortion for periods of more than [one] second as measured on any phase of the distribution line at point of connection of the small generator, otherwise the small generator shall immediately be disconnected.]

{The above paragraph may be omitted if it can be demonstrated that wave shape distortion dangerous to generator loads is an impossibility.}

3.5. Connection

The small generator shall only be connected to the distribution lines after it has been determined that all three phases of the distribution voltage are energized to within $1 \pm [0.1]$ per unit volts and the frequency is $60 \pm [0.1]$ Hz, for a period of [30] seconds.

3.6 Voltage Regulation

The distribution voltage at the point of small generator connection shall be controlled to within $1 \pm [.03]$ per unit. Excursion out of band shall be for no more than [60] seconds at just outside the band linearly scaled to [one] second at $1 \pm [0.1]$ per unit.

3.7 Voltage Balance

The balance shall be defined from the three phase to phase voltages as follows:

$$E_{ave} = \frac{E_{ab} + E_{bc} + E_{ca}}{3}$$

Unbalance in percent is the largest of:

$$\left| \frac{E_{ave} - E_{ab}}{100 E_{ave}} \right| \quad \text{or} \quad \left| \frac{E_{ave} - E_{bc}}{100 E_{ave}} \right| \quad \text{or} \quad \left| \frac{E_{ave} - E_{ca}}{100 E_{ave}} \right|$$

{NOTE: Single phase regulators may be required to control two phases independent of field control in order to maintain this voltage balance within safe limits.}

3.8 {If this section is included as part of the equipment specifications, the limit conditions defined in this section must be incorporated into the trouble check function (Section 6.4.4).}

4.0 REQUIREMENTS FOR DPU HARDWARE

4.1 MECHANICAL MOUNTING

4.1.1 {INTENT

It is the intent of these specifications to set further specific criteria for the well accepted standard 19" (483 mm) rack mount to permit physical interchange and/or mixing of modular units from various manufacturers.}

4.1.2 The mounting shall be based on the standard 19" (483 mm) rack. The height shall be 72" (1829 mm). {three types of cabinet/racks shall be standard, one should be chosen}. The mounting shall be by:

{Type 1:} [Open Rack, to be used in a separate room or otherwise protected from splashing or damage.]

{Type 2:} [Fixed Rack. This shall have a back door for access to wiring. The cabinet shall be EMI/RFI Shielded. Individual units shall be mounted flush with the front surface.]

{Type 3:} [Swing Rack Cabinet. This shall permit mounting with back against a wall and next to similar cabinets. The front door/equipment rack shall swing 180 degrees accessing wiring and shall include external terminal blocks mounted on the inside back wall. The cabinet shall be EMI/RFI Shielded.]

{Type 1 or 2 mounts may provide separate external terminal boards or optionally may require external wiring directly to rack mounted units.}

4.1.3 DEFINITION OF RACK UNIT

The unit mounting flange shall have tapped mounting holes on alternate $1/2"$ (13 mm) and $1 1/4"$ (31.7 mm) centers. A rack unit shall be defined as $1 3/4"$ (44.4 mm) in height and all modules shall have vertical dimensions an integral multiple of $1 3/4"$. Tolerance in vertical dimension shall be negative and there shall be no projections, screws, nuts, or otherwise extending beyond the multiple of $1 3/4"$ vertical dimension.

The unit width over all projections but exclusive of mounting flange shall be with negative tolerance only. The mounting rack opening shall be $17.75"$ (451 mm) with positive tolerance only.

The horizontal distance between holes shall be $18 5/16"$ $\pm 1/8"$ (465 mm ± 3 mm). Units shall have horizontal slots to accomodate this plus their own tolerance.

4.1.4 MAXIMUM FRONT PROJECTION FROM MOUNTING SURFACE

$1 1/2"$ (38 mm)

4.1.5 MAXIMUM UNIT DEPTH BACK OF MOUNTING SURFACE

$14"$ (355 mm) including terminal board and all projections.

4.1.6 VERTICAL CLEARANCE

{In order to allow mixing of English and metric modules the vertical dimension of a rack mounted unit shall be computed by one of the following formulas where R is the integral height in "rack units".}

$$\begin{aligned}\text{Vertical Dimension} &= [1.75 R - .05 \text{ in inches} \\ &= 44.45 R - 1.25 \text{ in millimeters}]\end{aligned}$$

4.1.7 TERMINAL BOARDS

[To face the back {in Type 1 or 2 mounts,} and mounted 14" (355 mm) back of the mounting flanges. The 14" to be maximum projection over the terminal board.]

[External terminal blocks to be mounted on the inside back wall] {of the Type 3 mount.}

External terminals to be mounted at [top or bottom] {per purchaser's choice.}

Terminals to run vertically and be numbered from top to bottom. If more than one. terminals to be lettered from left to right.

External terminal board, where in addition to unit terminals, to be designated AA, BB, CC etc.. Unit terminal boards to be designated A, B, C, etc. on each unit and units designated 01, 02, 03 etc.

from top to bottom. A typical unit terminal will then become 01A1.
See 4.1.13.

4.1.8 [Each mount to provide for location over a wiring trough with space for wires to pass through bottom of mount into the trough.]

4.1.9 [The top {of Type 2 or 3 mounts} should have clear space for conduit entrance.]

4.1.10 Barrier type terminal blocks suitable for #14 (64 mm) wire shall be provided.

4.1.11 The standard color for mounts and module panels shall be either ASA61 grey or brushed aluminum.

4.1.12 The mounting holes shall be tapped for #10-32 (M5) screws. {Note that for a shallow tapped hole, English and Metric screws of these sizes will be interchangeable.}

4.1.13 An RS232 output connector and a special 120 V ac power output connector which is keyed to match the maintenance unit cable (Section 5.0) shall be provided. These connectors shall be adjacent to each other.

4.1.14 Proposed Standard Mechanical Mounting

Dimensions in inches (millimeters)

4.2 DIGITAL PROCESSOR UNIT (DPU)

4.2.1 GENERAL

The DPU shall consist of a central processing unit, memory, interface devices, display and control panel battery power supply and firmware (Section 6.0) to provide the functions for fully automatic control of the Hydroelectric Plant.

An RS232 port shall be available for on site maintenance functions. Maintenance personnel shall be able to use this port to connect a terminal, dump the permanent data storage device (PDSD) and perform other tests as required.

The permanent data storage device shall perform two functions:

- a) Storage of status information.
- b) Storage of trouble information.

4.2.2 THROUGHPUT REQUIREMENTS

The DPU shall have 30% spare throughput capacity. This shall be determined over a one second interval during the peak time loading the DPU.

4.2.3 MEMORY REQUIREMENTS

Provision shall be made for, or memory provided for 30% additional RAM and 30% additional ROM beyond that needed for the defined requirements. If the memory is not provided with the system, spare card locations or sockets which are directly addressable without

additional wiring shall be provided to meet this requirement.

4.2.4 BI-DIRECTIONAL SERIAL MAINTENANCE PORT

The maintenance port shall meet the following requirements:

Electrical Interface: EIA Std RS232C. The connector shall be accessible from the front of the cabinet.

Character Coding: ANSI X3.4-1977 (ASCII - 1977)

ANSI X3.15-1976

ANSI X3.16-1978

Communication Control: ANSI X3.28-1976

The minimum data communication rate shall be 300 baud.

4.2.5 REMOTE COMMUNICATIONS PORT

The Remote Communications Port shall meet the following requirements:

Electrical Interface: EIA Std. RS232C. The connector shall be accessible from the back.

Character Coding: ANSI X3.4-1977 (ASCII-1977)

ANSI X3.15-1976

ANSI X3.16-1978

Communication Control: ANSI X3.28-1976

The minimum data communication rate shall be 300 baud.

4.2.6 PERMANENT DATA STORAGE DEVICE PORT

The Permanent Data Storage Device Port shall meet the following requirements:

Electrical Interface: EIA Std RS232C

Character Coding: ANSI X3.4-1977 (ASCII-1977)

ANSI X3.15-1976

ANSI X3.16-1978

4.3 DISPLAY AND CONTROL PANEL

A Control Panel shall be supplied which allows mode selections and control of Plant function when in the Manual Mode. The Control Panel shall meet the requirements of Section 4.1.

A typical control panel is shown in 4.3.1. The control panel shall follow the design philosophy suggested by this typical panel.

RESET LOCKOUT
REQUIRES KEY

STATUS LIGHTS

BREAKER

- OPEN
- CLOSED

WATER REGULATING VALVE

- FULL CLOSED
- OPEN TO SYNCHRONOUS
NO LOAD POSITION
- OPEN TO A
LOADED POSITION

9 9 9 9 9 9 9

ITCH

CK PROGRAM

on is for use with the Maintenance Unit. In this requested action shall be displayed on the Maintenance Cathode Ray Tube-video display), thus checking a the DPU without involving plant operation.

CK INPUTS

the following are typical checks.

external fault contact. Program should go to no load condition and wait for return of line

hot bearing contact. Program should execute soft shut

120 V ac to transducer with program in presynchronize

Program should show field raise or lower as input is

RATE SINGLE DEVICES

c device position shall permit operation of devices time from the Maintenance Unit. The DPU shall monitor tacts and only permit the device to operate if re safe. For example, the following is typical:

- o With input valve closed, operate wicket gates.

- o Trip and close breaker with proper inputs to electrical transducer simulating line and machine voltage, but only if disconnect switches are open.

4.3.2.4 MANUAL

The manual mode shall permit operation of the plant but will require manual operation of pushbutton switches (located on the lefthand side of the Typical Control Panel) to progress down the operating sequence. All pushbutton switches, with the exception of the "Reset Lockout" switch and the "Emergency Shutdown" switch, shall need only to be pushed but shall be effective only when the previous operation is complete. The "Reset Lockout" switch shall require a key to reset to "Normal Shutdown" after the trouble which led to the lockout condition has been corrected. The "Emergency Shutdown" pushbutton switch shall be operative at all times.

When a switch has been pushed, the adjacent "Action Started" light shall light. When the "Action Complete" light operates, the "Action Started" light shall extinguish, indicating a machine state ready to progress to the next state. The "Action Complete" lights, except for the auxiliaries (XXXX), shall extinguish after the next switch has been pushed. The "Action Complete" lights for the auxiliaries shall stay lit so long as they are operating. It may be desirable to have specific wording for the auxiliaries,

i.e. "oil pressure normal"; rather than the words "XXXX Normal" shown on 4.3.1.

4.3.2.5 AUTOMATIC

In the automatic mode, the control action shall proceed as in the manual mode but without operation of the switches which shall be ineffective.

NOTE: All lights shall operate at all times independent of the modes.

4.3.3 READOUT SELECT

This switch selects readouts as shown on 4.3.1.

4.3.4 MANUAL CONTROL SWITCHES

These are shown in a vertical column at the left edge of the panel on 4.3.1. The bottom switch shall require insertion and turning of a key to operate. The remaining are push button switches. The operation is described in 4.3.2.4.

4.3.5 ACTION STARTED AND ACTION COMPLETE LIGHTS

These shall be LED's operating as described in 4.3.2.4.

4.3.6 STATUS LIGHTS

These shall indicate the status of the circuit breaker and water regulating valve as shown on 4.3.1.

4.3.7 LAMP TEST SWITCH

It shall be possible to turn all indicator lights on with a single lamp test switch.

4.4 PERMANENT DATA STORAGE DEVICE (PDS)

4.4.1 GENERAL

The PDS shall be used for two functions:

a) Storage of regularly sampled status information as shown on Table 6.4.10.1 {This table is plant specific and must be formulated and included.}

b) Storage of trouble information in case of abnormal shutdown, as shown on Table 6.4.10.2 {This table is plant specific and must be formulated and included.}

4.4.2 MOUNTING

The PDS shall meet the requirements of Section 4.1 for 19" rack mounting.

4.4.3 STORAGE CAPABILITY

The PDS shall provide storage capability sufficient for 40 days of status information and one lockout shutdown record.

4.4.4 INTERFACE

The PDS shall meet the following interface requirements:

Electrical Interface: EIA Std. RS232C

Character Coding: ANSI X3.4-1977 (ASCII-1977)

ANSI X3.15-1976

ANSI X3.16-1978

4.4.5 DATA RETRIEVAL

The data stored on the PDSB shall be retrievable by two methods.

4.4.5.1 PROCESSOR CONTROLLED DUMP

The data shall be retrievable by transmission to the maintenance CRT or the remote data link.

4.4.5.2 STORAGE MEDIA REMOVAL

The data shall be retrievable by removing the storage media and replacing with a blank storage media.

4.5 POWER CONNECTION TO DPU

4.5.1 ELECTRICAL

Provision shall be made for standard 3 wire #14 120 V ac connection per NEMA code.

4.5.2 The 120 V ac input, hot and neutral, shall withstand 1500 V ac hi pot for one minute with respect to any other circuit or ground without damage.

4.5.3 One or more batteries shall be included capable of maintaining proper performance for [48] hours should the 120 V ac power be interrupted. A separate battery permanently wired to the real time clock circuit shall maintain time information for an accumulated time of one year without 120 V ac power with projected life of 10 years with 120 V ac power.

4.5.4 Single point grounding shall be provided by providing a chassis connection for the power ground (green wire) within 4" of a cabinet mounting hole or grounding stud.

4.5.5 Upon lowering of the battery voltage below a discharge threshold, the unit shall initiate a safe shutdown. The battery must have enough residual capacity to carry this shutdown to completion. Upon restoration of voltage above some higher "charged" level, the unit shall automatically return to normal operation.

4.6 REAL TIME CLOCK

A real time clock shall be included having a battery supply on the same printed circuit board (see 4.5.3). This clock shall be used for data recording and plant cycle initiation.

The clock shall give time information to the nearest second, corrected at the factory for all events including leap year for 100 years. The long term drift shall be less than 10 seconds per year. It shall be capable of being corrected (by a three position spring return switch or equivalent) by +1 second per switch operation.

5.0 MAINTENANCE UNIT

5.1 MOUNTING

The unit shall be in a 19" rack unit capable of either being mounted permanently in the rack with the DPU or in a portable case. When mounted in a portable case the blower, if required, and interconnection cable shall be out the front so that the unit will be completely covered and free of openings with the portable case cover on. The cover shall be completely removable.

The unit shall be sufficiently rugged to permit direct shipment as luggage on an airplane.

5.2 CRT

The CRT shall be at least 4" x 6" and capable of displaying at least 40 characters horizontally in 20 lines of text. Characters may be upper case only. The English alphabet, numbers 0 to 9 and symbols required to display the program and maintenance information shall be included as a minimum capability.

5.3 CONNECTORS

The connector shall be capable of insertion and removal with the DPU on without damage or interruption of DPU operation. All data exchange to the maintenance unit shall be by one RS232 cable and connector. A power cord shall be provided which is compatible with the 120 V ac output provided on the DPU cabinet.

5.4 CAPABILITY

With the control panel mode switch in the "Check Program" position, the control panel shall operate as in the manual mode except that suitable CRT display will result rather than plant operation.

With the mode switch in the "Check Inputs" position, it shall be possible to select and display at least the following:

- Status of any contact.

- Value of any electrical quantity from Type D device.

- Value of all setpoints.

- Value of all analog inputs and outputs.

- Values of any table look up quantities stored in memory.

- Data from the Permanent Data Storage Device.

With the mode switch in the "Operate Single Device" position, it shall be possible to select and control any single device. The DPU shall monitor status inputs and permit manual operation of a single device only under safe conditions.

With the mode switch in the "Manual" or "Automatic " position, a block of data deemed useful for each machine state, shall be formatted and displayed. For example, prior to synchronizing the format might, as a minimum, be as follows:

- Machine State: Ready to Synchronize

- Line Voltage: xxx

- Machine Voltage: xxx

- ΔE : xxx

Phase angle in degrees: xxx

Line Frequency: xxx

ΔF : xxx

Headwater Level: xxx

Tailwater Level: xxx

6.0 DPU Programs

6.1 PROGRAMMING LANGUAGE

The program shall be written in Pascal (Ref. 4, 5, 6) with high level language in strict compliance with ISO proposed standard 7185 submitted to ANSI on May 19, 1980 or the revised version accepted by ANSI. The program shall be compiled and shall operate in one of two ways:

a) Compiled to a P-code (psuedo machine code) and operated thru a firmware translator to the machine code for the specific microprocessor being used. The P-code shall comply with ISO proposed standard 7185 submitted to ANSI on May 19, 1980 or the revised version accepted by ANSI.

b) Compiled to the machine code for the specific microprocessor being used.

6.2 PROGRAM PERFORMANCE SPECIFICATION

The vendor shall submit a Program Performance Specification (PPS) for approval by the purchaser. The PPS shall define the operations that shall be performed by the processor to meet the requirements of this document.

The PPS shall define as a minimum the following:

6.2.1. Program Structure: Define and name all call routines, subroutines, and procedures.

6.2.2 Labeling: Define standard labeling method for all call routines, subroutines, and procedures.

6.2.3 Program Flow: Define entry and exit points and criteria for entry and exit for all call routines, subroutines and procedures.

6.2.4 Timing: Define execution sequence and calculate worst case execution time for all call routines.

6.2.5 Description of call routines, subroutines, and procedures: Each call routine, subroutine and procedure listed in 6.2 shall be described to the detail necessary to insure that the program meets the requirements of this document. This shall include as a minimum:

6.2.5.1 Define all constants including type and precision.

6.2.5.2 Define all variables including type and precision.

6.2.5.3 Identify all feedforward and feedback loops, point of exit, point of entry, and direction of flow.

6.2.5.4 Define separately each input and output data function.

6.2.5.5 Define separately each processing function which executes defined operations resulting in a change in value, form or location of information or in determination of which of several flow directions are to be followed.

6.2.5.6 Human Interface: Provide definitions of all syntax and format which are used in communications with any peripheral device.

The PPS shall be submitted for approval before start of detailed programming.

6.3 PROGRAM ACCEPTANCE TEST PLAN

The vendor shall supply a detailed program acceptance test plan for approval by the purchaser. This test plan may be incorporated as part of the equipment test plan.

6.4 PROGRAM REQUIREMENTS

6.4.1 GENERAL

The programs for the DPU will provide capability to operate in five modes:

- a) Check Program.
- b) Check Inputs.

- c) Operate Single Device.
- d) Manual.
- e) Automatic.

{A set of typical flow charts describing plant operations is shown in Sections 6.4.1.1 through 6.4.1.9. Each plant will have different requirements and the flow charts should be modified as necessary to meet these requirements.}

Additional requirements which shall be incorporated irrespective of modifications to the flow charts are defined in Sections 6.4.2 through 6.4.12.

6.4.1.1 Overall Operation

6.4.1.2 Overall Operation (Cont.)

1.3 Start Detail

6.4.1.4 Start Detail (Cont.)

6.4.1.5 Synchronize Detail

6.4.1.6 Load & Regulate Detail

6.4.1.7 Typical Regulate Detail (Δf , ΔE , Watts, VARs)

6.4.1.8 Shutdown Detail

6.4.1.9 Shutdown Detail (Cont.)

6.4.2 DATA INPUT

The Data Input function is defined as reading all of the data from I/O modules and transferring it to memory where it will replace previous data for computation or test or will be transferred to the Permanent Data Storage Device.

The Data Input function shall have two divisions: High Speed (HSDI) Low Speed (LSDI).

If multiple data words are available from a single input module, the Data Input function requires transfer of all data words during one Data Input cycle.

The Data Input function shall meet the following requirements:

	RATE	STABILITY
HSDI	100 cycles/sec minimum	1%
LSDI	1.0 cycle/sec minimum	5%

{Note that some inputs must be sampled at rates which depend on the machine state. For example phase angle across the open breaker must be sampled 100 times a second while synchronizing, and is not sampled at all when not synchronizing.}

6.4.3 DATA OUTPUT

The Data Output function is defined as reading all of the output data from memory and transferring it to the appropriate output

module. The Data Output function shall have two divisions: High Speed (HSDO) and Low Speed (LSDO).

If multiple data words are required for a single output module, the Data Output function requires transfer of all data words during one cycle.

The Data Output function shall meet the following requirements:

	RATE	STABILITY
HSDO	100 cycles/sec minimum	1%
LSDO	1.0 cycle/sec minimum	5%

6.4.4 TROUBLE CHECK

The Trouble Check function shall test all input data from the plant to determine if an operational problem has occurred and to classify the problem as a Major Trouble, a Minor Trouble, or a Warning Trouble.

The testing shall be performed by comparing input data with predefined limits (continuous) or with predefined status words (discrete).

{The test points and resulting classification shall be supplied as an attachment to this specification.}

The Trouble Check function shall be performed at a minimum rate of [1.0] Hz.

6.4.5 SELF TEST

The processor shall perform a complete Self Test while operating in any modes.

The Self Test shall as a minimum test the following functions:

6.4.5.1 Test all internal data paths - Test with "1"s and "0"s.

6.4.5.2 Test all working registers - Test with "1"s and "0"s.

6.4.5.3 Non-volital memory (ROM) - Test by a right bit checksum of all non-alterable memory locations.

6.4.5.4 VOLITAL MEMORY (RAM)

Method 1 - Test all Program Memory locations with alternating "1" and "0" words; i.e. each 8 bit memory location shall be tested with hexadecimal "55" followed by hexadecimal "AA". The Self Test shall be executed at a minimum rate of once every 4 minutes.

Method 2 - Provide memory which has parity check.

6.4.6 SEQUENCE CONTROL

The Sequence Control function shall initiate normal Plant startup and shutdown based on any of the following inputs: Time of Day, Forebay Water Level, Afterbay Water Level, Command from Remote

Terminal. Command from Run of River Control Computer, Manual Input.

The Sequence Control function shall be used in the Automatic Mode.

6.4.7 STARTUP

The Startup function shall sequence through all of the necessary steps to bring the Plant from a total "off" status through synchronization. This shall include control functions and status checks to perform the sequence illustrated in Section 6.4.1.3.

6.4.8 PRESYNCHRONIZING CONTROL

6.4.8.1 VOLTAGE CONTROL (PRE-SYNCHRONIZING)

The Voltage Control function shall control the generator field voltage as a function of the difference between generator measured voltage and power network voltage.

The field voltage shall be controlled by two discrete outputs; "x" and "y". The field voltage shall increase or decrease at a constant rate while "x" or "y" respectively are enabled.

The Voltage Control equation shall be:

$t_r = K(E_l - E_g)$; x output in seconds

$t_l = K(E_g - E_l)$; y output in seconds

K to be supplied by the manufacturer of the field control as rate

of change of field voltage in per unit volts per second.

E_l = Line Voltage

E_g = Generator Voltage

The Voltage Control Function shall be executed once every [2] seconds when in use.

6.4.8.2 FREQUENCY CONTROL

The Frequency Control function shall control governor position as a function of the difference between the measured generator frequency and the measured line frequency.

The governor position shall be controlled by two discrete outputs; "x" and "y". The gate shall open or close at a constant rate while output "x" or "y" respectively is enabled.

The Frequency Control equation shall be specified by:

$t_o = K \Delta f$ for negative Δf

$t_c = K \Delta f$ for positive Δf

t_o = duration of x output in seconds

t_c = duration of y output in seconds

Δf = difference between generator frequency and power network frequency. Positive Δf indicates that generator frequency is higher than power network frequency

K = proportionality constant provided by the manufacturer of the

governor as change in frequency in hertz per second.

The Frequency Control function shall be executed once every [10] seconds until Δf and ΔE are within synchronizing limits. When synchronizing limits are realized, the Breaker Control Contact shall be closed for angles within a window determined by:

$$\delta = 360 * \Delta f_m \text{ (in degrees)}$$

δ = advance angle in degrees.

6.4.9 RUN

6.4.9.1 POWER OUTPUT CONTROL

The Power Control function shall control gate position as a function of the difference between the measured output power (P_o) and the setpoint output power (P_s).

The gate position shall be controlled by two discrete outputs, "x" and "y". The gate shall open or close at a constant rate while either output "x" or "y" respectively is enabled.

The equation for the x output shall be:

$$t_x = K(P_s - P_o)$$

t_x = duration of output raise contact closure in seconds

P_o = measured generator output in kW

P_s = setpoint generator output in kW

K = proportionality constant provided by the manufacturer of the governor as rate of change of governor setting in kW per second.

The equation for the y output shall be:

$$t_y = K(P_o - P_s)$$

t_y = duration of the y contact closure in seconds.

The power control function shall be executed once every [10] seconds. {This time should be approximately 3 times the machine speed response time constant}.

6.4.9.2 VAR CONTROL

The VAR control function shall control the generator field voltage as a function of the difference between measured VARS and desired VARS.

The field voltage shall be controlled by two discrete outputs; "x" and "y". The field voltage shall increase or decrease at a constant rate while "x" or "y" respectively are enabled.

The VAR control equation shall be:

$$t_r = K(VAR_m - VAR_s)$$

$$t_l = K(VAR_s - VAR_m)$$

t_r = x output to raise VAR

t_l = y output to lower VAR

VARm = measured VAR

VARs = setpoint VAR

K = proportionality constant specified by the manufacturer of the generator field control in per unit change in VAR per second.

The VAR Control function shall be executed once every [0.5] seconds when in use.

6.4.9.3 [BLADE CONTROL]

{Note: Not all machines have a variable pitch rotary blade}

The Blade Control function shall control the runner blade position as a function of headwater level, tailwater level and output power.

The blade position shall be controlled by two discrete outputs; "x" and "y". The blade shall move in one direction or the other at a constant rate while outputs "x" and "y" respectively are enabled.

The control shall have a dead band of [2]% of the kW setpoint. A [10] second timer shall start when the generator output goes above or below the band edges. When the timer times out, the blade shall move so as to return the output to as close to the center of the deadband as practical. If the output returns to the band before the timer times out, the timer shall reverse direction to a possible reset; or so that the final time out is the integral of the time in and out of the band.

The Blade Control function shall be executed once every [10] minutes.

6.4.10 PERMANENT RECORDING AND RETRIEVAL

6.4.10.1 STATUS INFORMATION

The status information recorded shall be:

- [A. Time of Day:
- B. Time of Day when breaker opens or closes:
- C. Date:
- D. Output Voltage:
- E. Setpoint Output Power:
- F. Measured Output Power:
- G. Average Output Power since previous record:
- H. Setpoint VAR:
- I. Measured VAR:
- J. Station Status (Startup, Run, Shutdown):
- K. Kwh since last reading:
- L. Kwh since startup:
- M. Kwh since last reset to zero:
- N. Control Device Enabled:
- O. Forebay Water Level:
- P. Afterbay Water Level:

Others as required]

6.4.10.2 TROUBLE INFORMATION

In the event of trouble, the DPU shall record the following:

- [A. Time of Day
- B. Date
- C. Trouble Condition (from Protective Relay equipment)
- D. Contact Monitor Status Previous to Fault
- E. Others as desired]

6.4.10.3 DATA RETRIEVAL

The program shall provide the capability to transfer the data from the PSDS to the Maintenance Device for display.

6.4.11 MAN/MACHINE INTERFACE (MMI)

6.4.11.1 GENERAL

The MMI shall be provided through the Maintenance Terminal (MT). Selection of any set point or function operator input shall result in visual feedback at the MT. The operator input to the MT shall be recognized and acknowledged within one second.

6.4.11.2 CONTROL PANEL/DISPLAY PANEL

The DPU shall update all functions on the Display Panel in all modes of operations. This function shall be performed at a minimum rate of 10 per second.

When the Control Panel is the selected Control Device, the Control Panel switches and set point controls shall be monitored for new operator input at a minimum rate of 10 per second.

During all modes of operation, the "Emergency Shutdown" switch shall be monitored at a minimum rate of 10 per second.

6.4.11.3 MAINTENANCE TERMINAL

The MMI using the Maintenance Terminal shall be executed using a menu selection process and interactive dialogue. The DPU shall provide the capability for an operator to select any of the modes and control any of the functions which are provided for on the Control Panel through the Terminal. The DPU shall also provide Operator selections of desired status outputs for display on the Terminal.

These operations shall be performed only when the Terminal is the selected Control Device.

6.4.12 SHUTDOWN

Shutdown shall be performed based on the results of the Trouble Test functions or on command from the Control Device or as a normally programmed function. The shutdown sequence is illustrated in Figure 6.4.1.8.

7.0 PLANT PERIPHERAL DEVICES

7.1 COMMON REQUIREMENTS

7.1.1 MECHANICAL

7.1.1.1 Each device shall be mounted in an EMI/RFI Shielded oil tight JIC box.

7.1.1.2 It shall be possible to easily remove the inner panel which shall include all components and terminal boards so as to mount the box and run conduit and wires with panel out of box.

7.1.1.3 One box may house more than one device if desired.

7.1.2 POWER CONNECTION

7.1.2.1 ELECTRICAL

Provision shall be made for standard 3 wire #14 connection per NEMA code.

7.1.2.2 Single point grounding shall be provided by providing a chassis connection for the power ground (green wire) within 4" of a cabinet mounting hole.

7.1.2.3 The power input circuits shall withstand 1500 V ac hi pot with respect to any other circuit.

7.1.2.4 The power input circuit shall meet ANSI-C37.90a-1974 Surge Withstand Capability.

7.1.2.5 Each battery charging transformer shall have a rating of the maximum energy in Joules at all frequencies which may be passed from primary to secondary by a 0.1 second transient of any magnitude and frequency spectrum. Secondary protection shall be provided to by-pass this energy level, holding voltage levels to a safe value for circuitry contained within.

7.1.2.6 A single battery in each unit shall be included capable of maintaining proper performance for [48] hours should the 120 V ac power be interrupted.

7.1.2.7 The units shall perform properly over a temperature of -40 to +80 degrees C. Proper operation shall be obtained with humidity from zero to 100%; including rain or snow.

All semiconductors shall be hermetically sealed. Plastic cases are not acceptable.

All switches and connectors shall have gold plated contacts.

7.1.2.8 Upon lowering of the battery voltage below a discharge threshold, the unit shall initiate a safe shutdown. The battery must have enough residual capacity to carry this shutdown to

completion. Upon restoration of voltage above some higher "charged" level, the unit shall automatically return to normal operation.

7.2 Type A: The purpose of this device shall be to perform a control function in response to computer commands received from the DPU via a fiber optic cable and I/O Modules for commandable output states which are initially defined by programming a DIP switch.

7.2.1 OUTPUT STATE DEFINITIONS #1

Normal: Both relays dropped out.

x: Relay x picked up

y: Relay y dropped out

Emergency: Upon loss of power (battery discharged) or upon interruption of continuous flow of commands from the fiber optic input, both relays shall drop out.

7.2.2 OUTPUT STATE DEFINITION #2

Normal: Relay x dropped out, relay y picked up.

x: Relay x picked up

y: Relay y picked up

Emergency: Upon loss of power (battery discharged) or upon interruption of continuous flow of commands from the fiber optic input, both relays shall drop out.

NOTE: In applying this unit to provide fail safe emergency shutdown, with a failure the first alternate will run the

controlled device to one extreme, the second alternate will leave it where it was.

7.2.3 Inputs: Fiber optic cable.

120 V ac power.

7.2.4 Outputs: One C contact per relay.

Contacts used to switch d-c circuits shall be capable of making and breaking 150 V dc, one amp inductive. To accomplish this, the output circuit shall be as follows:

All terminals shown above shall withstand 1500 V ac 60 Hz to chassis for one minute without damage. The output contacts shall close within 5 ms after receiving a command from the DPU.

7.3 Type B: The purpose of this device is to report to the computer the rotational position of plant components.

7.3.1 Mechanical coupling to plant component will be by a 1/4" shaft.

7.3.2 Angular Rotation: Full scale rotation shall be from 180 to 360 degrees.

7.4 TYPE C CONTACT MONITOR

This device shall be capable of monitoring up to eight contact closures.

7.4.1 INPUTS

Each of eight inputs shall be from a contact indicating status of an end device. The contact shall be sensed with from 12 to 24 V dc with at least 15.0 mA flowing when closed, supplied from the device. One side of each contact shall be common.

7.4.2 POWER

120 V ac per common requirements

7.5 TYPE D TRANSDUCER

This device shall develop all of the required voltage current and power flow inputs to the computer. Nominal 120 V ac from [] line potential device [s]

Nominal 120 V ac from [] generator potential device [s]

[] Inputs, each nominal 5 amps and capable of withstanding 100 amps for one second.

120 V ac battery charging source shall be from one line potential device.

All 120 V ac inputs shall meet the general requirements stated above.

{Show from 1 to 3 of each device where brackets are shown.}

7.5.1 OUTPUTS VIA OPTICAL CABLE

7.5.1.1 Line Volts; 0 to 150 V ac $\pm 0.3\%$

7.5.1.2 Scaler difference between Line and Generator voltage, range 0 to 25 V ac ± 0.5 volts.

Above with true rms detection and up to 5% total harmonic distortion containing up to 9th harmonic.

7.5.1.3 Kilowatts; 0 to 1.1 p.u. ± 0.01 p.u.

7.5.1.4 Kilovars; 0 to 0.6 p.u. ± 0.01 p.u.

With voltages within 10% and current 0 to 5 amps

7.5.1.5 Δf (frequency difference across breaker) 0 to 0.5 Hz
.005 Hz full scale; for frequencies from 55 to 65 Hz

7.5.1.6 Machine Frequency: 55 to 65 Hz ± 0.05 Hz
{Or preferably shaft rpm; 0 to max possible speed}

7.5.1.7 Phase angle: 0 to 90 degrees ± 2 degrees

7.5.1.8 Breaker Position (Open or Closed)

7.6 TYPE E ANALOG OUTPUT DEVICE

This device shall furnish electrical analog output signals as may be required by related systems (for example a SCADA system) not otherwise described in this document.

7.6.1 INPUTS

The input may be from the microprocessor bus if the related system is located in the same or an adjacent cabinet and rack and if the power source, use of battery and fiber optic cable techniques are in accordance with these specifications.

Otherwise, the input shall be by a fiber optic cable per common requirements and using data transmission as per Section 8.4.

7.6.2 POWER

120 V ac per common requirements (if microprocessor bus is not used).

7.6.3 OUTPUTS

Choice of 0 to ± 10 V dc full scale into 1000 ohms or greater or:
Alternate of 0 to ± 1 mA full scale into 1000 ohms or less.

7.6.4 ACCURACY

$\pm 0.5\%$ of full scale.

7.7. TYPE F ANALOG INPUT DEVICE

This device shall translate electrical analog inputs to digital data acceptable to the microprocessor.

7.7.1 INPUTS

Choice of 0 to ± 10 V dc full scale.
Burden to be 1000 ohms or greater or:
Alternative of 0 to ± 1.0 mA full scale.
Burden to be 1000 ohms or less.

7.7.2 POWER

120 V ac per common requirements

7.7.3 OUTPUT

Serial digital data via fiber optic cable with data transmission as per Section 8.4.

7.8 POTENTIAL TRANSDUCER

Resistive Potential Devices (RPD) are available today. If used, these shall be connected to the Type D device as follows, referring to 7.7.

7.7 Connections for RPD

8.0 COMMUNICATIONS INTERFACE SPECIFICATIONS

8.1 FIBER OPTIC INTERFACE

All interdevice communications shall be by fiber optic cables. (Ref. 7, 8, 9, 10) The optical transmitter, receiver, and terminated cable shall be supplied as a unit with a guaranteed bit error rate of less than 10 at a 25 kilobit rate, over a temperature range from -40 to +89 degrees C.

8.1.1 STANDARD LENGTHS FOR FACTORY TERMINATED FIBER CABLES

1 meter

2 meters

4 meters

8 meters

16 meters

32 meters

64 meters

100 meters

200 meters

400 meters

800 meters

Lengths up to 5 Km cut and terminated to order.

8.1.2 Each link shall be operated in a continuous mode so that a cable break or device failure will be detected immediately.

8.1.3 [Fiber optic cable shall be suitable for direct burial in sand outdoors.] The cable shall be capable of withstanding direct sunlight for 25 years without failure. The minimum size PVC conduit inside diameter shall be furnished which will pass the connector with up to [4] cables already in the conduit. Manufacturers minimum bend specifications shall be provided.

8.2 PLANT I/O MODULES

The Plant I/O Modules shall provide the interface between the fiber optic cable and the DPU.

8.2.1 MECHANICAL

The module shall consist of fiber optic connectors, printed circuit board, a connector to interface to the DPU parallel data bus and electronics necessary to provide the serial/parallel conversion, communications control, electronic interface to the bus and electro optical energy conversion.

8.2.1.1 FIBER OPTIC CABLE CONNECTORS

One Fiber Optic Cable Connector shall be provided for each serial transmitter or receiver. Attachment of the fiber optic cable connector shall be a screw on or clamp procedure which can be performed by a technician.

8.2.1.2 PRINTED CIRCUIT BOARD AND CONNECTOR

The board and connector shall be compatible with the DPU bus

system.

Components on the board shall be organized to allow connection or disconnection of the fiber optic cables without removal or damage to any other components.

8.3 COMMUNICATIONS AND CONTROL

8.3.1 TRANSMITTED DATA

The data input from the DPU bus shall be continuously retransmitted to the Plant Peripheral Devices. The rate of retransmission shall be as defined under the specific device specification. The transmission of data shall be transparent to the DPU.

The data transmission error rate shall not exceed one error in 10^{-9} bits. Error correcting codes shall be allowed to obtain this rate.

8.3.2 RECEIVED DATA

The received data shall be continuously updated by the Plant Peripheral Device. The received data shall be continuously checked for transmission errors.

If two or more errors are detected within [two] adjacent transmission blocks, a flag shall be provided to the DPU to enable a fault sequence.

The parallel output available to the DPU shall be continuously

updated at the rate of retransmission unless an error is detected, in which case the previous data shall remain available to the parallel DPU bus. The updating of the parallel output shall be transparent to the DPU.

8.4 INTERFACE WITH MICROPROCESSOR PROTECTIVE RELAY (Ref. 11)

This shall be by means of two fiber optic cables for bidirectional data transfer. The protocol shall meet the requirements of synchronous data link control as defined in the IBM General Information Manual GA27-3093-0.

When data is transmitted in either direction, the correct receipt of the data shall be acknowledged.

If the data link goes to the idle mode, the DPU shall immediately retransmit the last data. This shall insure that the data link is intact and operating correctly.

If an error is detected for two sequential attempts, a fault condition shall be signaled to the DPU.

9.0 AUTOMATIC SYNCHRONIZER

9.1 CONTROL FUNCTIONS

The following controls shall be available for easy adjustment and shall not require external equipment for settings within the accuracy specified.

9.1.1 Upper Voltage Limit for both potential inputs shall be variable from a minimum 110 to 140 V ac accurate to within $\pm 2\%$ of full scale.

9.1.2 Lower Voltage Limit for both potential inputs shall be variable from a minimum 90 to 120 V ac accurate to within $\pm 2\%$ of full scale.

9.1.3 Differential Voltage Limit shall be variable from a minimum 1 V ac to 10 V ac. Accuracy shall be better than $\pm 5\%$ of the full scale voltage difference.

9.1.4 Differential Frequency Limit shall be variable from a minimum of .05 Hz to 0.5 Hz. Accuracy shall be within $\pm 5\%$ of full scale.

9.2 FEATURES

9.2.1 The automatic synchronizer shall offer programmable breaker closing time which will accomodate a breaker with closing time from

0 to 800 ms with steps no greater than 20 ms.

9.2.2 Output close circuit shall be capable of closing 20 amps at 250 V dc minimum and shall be electrically isolated from each of the potential inputs and the power source input.

9.2.3 Power source input burden shall be no more than 5 VA.

9.2.4 Potential input burdens shall be no more than 0.5 VA.

9.2.5. The unit shall close with a phase angle accuracy, calculated as follows:

$$\delta_s = 78.7 (t_f) \left(\frac{\text{pf} \times \underline{X_t}}{H} \right)^{\frac{1}{2}} \quad \text{maximum allowable closing angle in degrees.}$$

where

δ_s = phase angle error at instant circuit breaker contacts close.

t_f = fault clearing time in seconds

$\underline{X_t} = \underline{X_g''} + \underline{X_l}$, all in per unit

H = generator inertial constant

pf = rated machine power factor

$\underline{X_g''}$ = per unit generator subtransient reactance

$\underline{X_l}$ = per unit line reactance to an equivalent infinite

generator. This should be the lowest value from several line configurations if such is possible with various network breaker states (states means configurations of breakers open and

closed).

9.3 ENVIRONMENTAL

9.3.1 The automatic synchronizer shall perform to the above mentioned specifications and accuracy within a minimum temperature range of -40 to +80 degrees C.

9.3.2 The automatic synchronizer shall perform to the above mentioned specifications and accuracy under high humidity conditions with relative humidity greater than 90%.

9.4 RELIABILITY & MAINTAINABILITY

9.4.1 The automatic synchronizer shall be constructed of high quality components; no plastic semiconductors or plastic integrated circuits shall be used.

9.4.2 Finite life components, such as large electrolytic capacitors, incandescent bulbs, etc., shall offer a minimum expected life of 5 years when operated continuously and at "worst case" environmental conditions.

9.5 ELECTRICAL

9.5.1 Potential inputs and power source inputs shall be transient protected. Inputs shall pass Hi Pot 1500 V ac to ground for a

minimum of one minute, and shall withstand transients with an available energy of 15 joules minimum.

9.5.2 The circuit design shall be such that general component failures shall not cause false breaker operation. The circuit design shall be such that internal power supply failure shall not cause false breaker operation.

9.5.3 The automatic synchronizer operation shall include circuits which will allow breaker closure only one time; removal of power source input for 10 seconds shall reset the automatic synchronizer for another breaker closure. A front panel indicator shall indicate when the automatic synchronizer is ready for breaker closure.

9.6 SETTINGS

The automatic synchronizer shall close a status contact when voltage conditions are within the set limits and a second status contact when Δf conditions are within set limits.

9.6.1 The frequency difference shall be set as follows:

$$\Delta f_s = \frac{3(t_f)(pf)}{H} \quad \text{maximum allowable frequency difference in Hertz.}$$

9.6.2 The voltage difference shall be set as follows:

$$\Delta E = \frac{X_t}{30} \sqrt{1 - (pf)^2}$$

ΔE = per unit voltage difference.

{It is suggested an adjustable range 20% higher and lower than the values calculated for Δf and ΔE be specified in sections 9.1.3 and 9.1.4. Recognize the manufacturers will likely supply a standard range covering the specified range and more.}

Note: In 9.2.5, 9.6.1, and 9.6.2, the following identify the variables.

$X_t = X_g'' + X_l$, all in per unit.

t_f = fault clearing time in seconds

H = generator inertial constant in joules per volt ampere

pf = rated machine power factor

X_g'' = per unit generator subtransient reactance

X_l = per unit line reactance to an equivalent infinite generator.

This should be the lowest value from several line configurations if such is possible with various network breaker states (states means configurations of breakers open and closed).

{See two reference papers on synchronizer Δf settings and required phase angle accuracy. These are included in Section IX of the Appendix since they are unpublished.}

9.6.3 The breaker closing time adjustment shall be made to agree with the rated closing time of the breaker or better yet with the measured closing time of the breaker.

10.0 DOCUMENTATION

10.1 STANDARD DRAWING SIZES

Each Drawing shall be one of the following sizes:

- A. 8 1/2" x 11"
- B. 11" x 17"
- C. 18" x 24"
- D. 24" x 36"
- E. 36" x 54"

10.2 SCHEMATICS

Schematics shall conform to the latest revision of ANSI Y14.15-1973, ANSI Std 91-1973 and ANSI Std 315-1975.

10.2.1 Inputs shall be to the left, outputs to the right. Positive voltages shall be to the top, negative to the bottom. To every extent possible, information shall flow from left to right except feedback paths which shall flow from right to left.

10.3 External Connection Diagrams shall clearly label each connection required when the equipment is installed.

10.4 Mechanical drawings shall be dimensional in both English and metric units and shall show outline dimensions, mounting holes, door swings, and any other information necessary or useful in installation.

10.5 Computer Program Flow Diagrams shall conform to ANSI X3.5-1970.

10.6 Block Diagrams shall be connected by single lines showing flow of information and be in sufficient detail for clear understanding.

10.7 Parts Lists shall have sufficient detail for replacing all electrical and those mechanical parts subject to wear, loss, or breakage. The parts shall be listed in the smallest breakdown practical for field replacement.

A complete history of all drawing changes made after first shipment of equipment shall be kept on the drawing.

10.8 MAINTENANCE MANUAL

This shall contain as a minimum the following:

1. Theory of operation description.
2. Specifications and limitations.
3. Block diagrams.
4. Suggested maintenance.
5. Calibration and troubleshooting procedures.
6. Schematic diagrams.
7. Physical component placement diagrams.
8. A bill of material list of all components.

The block diagrams, schematic diagrams, and theory of operation description shall all be cross-referenced so that areas described can be easily identified on both block and schematic diagrams.

Components shall be identified such that they can be cross-referenced on schematic diagrams, physical layout diagrams, and bill of material lists. All components must be listed on the bill of material list. The parts shall be listed in the smallest breakdown practical for field replacement. Each component must be identified by a part number by which it can be ordered from the manufacturer and a second source supplier. Maintenance procedure descriptions will specify all recommended calibration and routine maintenance procedures, as well as a recommended maintenance schedule.

10.9 A list of recommended spares shall be included. Each spare shall be at a level of subassembly practical for field replacement.

10.10 A set of final computer program descriptive material as specified in Section 6 shall be supplied.

11.0 Drawing Submittal

11.1 Schematics, mechanical outline drawings and external connection drawings shall be submitted for approval prior to start of manufacture.

11.2 A Computer Program Performances Specifications as defined in Section 6.2 shall be submitted for approval prior to start of programming.

11.3. Final versions of above together with schematics, parts lists, parts location drawings and other drawings required for maintenance shall be furnished with shipment of the equipment.

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III. APPENDIX

A.I.

INTRODUCTION

It is the primary goal of this report to anticipate trends in the rapid development of microprocessor technology and establish specifications which compliment these trends so as to make hydropower automation a natural part of the technological growth. In this way it is believed the application of microprocessors to hydro automation will have the greatest benefit at lowest cost. Moreover, it seems vitally important to keep hydro automation as a part of the greater technological growth and not an isolated technology in order that benefits from the greater growth area can continue to flow to the hydro application without technical barriers to hurdle.

The more detailed specifications which are included therefore follow these overall trends.

THE INDUCTION GENERATOR

Induction generators may be used with ratings up to about 2 MW. These machines produce no voltage without being tied to a network containing other generators. A possible exception to this is found if capacitors are tied to the generator and the generator has previously been tied to a source of voltage.

An induction generator takes lagging reactive current from the system for its excitation the same as an induction motor. In fact the only basic difference is that an induction generator is driven by a prime mover at higher than synchronous speed and an induction motor delivers mechanical output energy at lower than synchronous speed.

The induction generator excitation must be provided either by synchronous generators or by static capacitors. If by capacitors a question arises whether to connect onto the load or generator side of the generator breaker. Problems are introduced either way.

CAPACITORS ON LOAD SIDE

Here the problem of machine automation is made easy since it is known that the generator voltage will die to zero within a few seconds after the breaker opens. Referring to Diagram 1.2.6, the automatic synchronizer may be omitted. The Digital Processor Unit (DPU) can then command breaker closing when the line voltage and frequency are within tolerance and when the machine speed matches the line frequency within tolerance.

For the DPU to know the machine speed, it will be necessary to provide a tachometer, not shown on 1.2.6, to provide this DPU input.

A second redundant breaker closing contact should be provided to prevent either one of the following:

a) Closing a stopped generator into a line. The generator would start as an induction motor with possible mechanical damage to the machine and possible undesired or even dangerous lowering of the line voltage. A reverse power relay could trip the breaker but damage could already have occurred.

b) Closing a running generator into a dead line. Static capacitors on the line together with residual generator field could cause the generator voltage to build up to an unknown level and frequency with unexpected and possibly dangerous results.

This redundant closing contact could be a relay picked up by a series combination of a line voltage sensitive relay and a tachometer under speed contact. This would provide a crude but safe duplication of the DPU action and further guard against improper closing of the breaker.

Since an induction machine has no field, the field control shown on 1.2.6 would be eliminated.

The induction generator exciting capacitors may cause an undesired voltage rise when the generator breaker opens. This may require a second breaker to open the capacitors, either as a function of line voltage or simultaneously with the generator breaker. If by line

voltage, the control could be a DPU function. In other words, with the generator off line, the DPU could provide voltage sensitive switching of the capacitor breaker.

CAPACITOR ON THE GENERATOR SIDE

This arrangement could save one breaker but will complicate the control. The greatest problem is that little is known either experimentally or theoretically about the frequency and voltage which may exist with the generator breaker open.

It should be possible to provide an automatic synchronizer less the usual voltage constraints and close in a manner similar to a synchronous machine. It would be necessary to provide an alternate closing path for the case where the generator voltage is less than, say 0.2 PU. At that level the inrush current should be no more than 1.2 times the normal exciting inrush with machine voltage at zero. This method is not recommended without additional knowledge, both practical and theoretical.

AN INDUCTION GENERATOR TIED TO A DISTRIBUTION LINE

This could be the most advantageous application of an induction generator. The induction generator could maintain proper voltage at its point of coupling to the circuit. Voltage switched capacitors could maintain proper voltage at other points on the distribution circuit and correct power factor as well. Here the cost of the

capacitor switching is justified both as a means of maintaining voltage and for providing exciting current for the induction generator.

RIVER FLOW COMPUTER

Often a number of hydro plants will be located along the same river. Here the obvious but non trivial problem exists that all the water must eventually move somewhere. The water movement may be complicated by the amount of pond storage above each dam, water diverted for irrigation and evaporation.

The desired generation is influenced by load near each generator even though loads are interconnected since it is desirable to minimize line losses. These requirements may conflict with those for water flow.

Extensive programs for optimizing generation and still meeting pond level and irrigation requirements, have been written. Even if complex, these programs need not run rapidly. It therefore appears that the computer for this use can be a duplicate of those used for machine automation. This will minimize initial cost, cost of spares, and maintenance cost in general.

One visualizes, therefore, a river flow control computer whose inputs are headwater level at each dam and irrigation requirements, if any. In the simplest form, the computer would transmit kW setpoints to

each machine and perhaps controls to nongenerating spillway gates. It would thus control headwater level within established limits.

Communication cost can obviously be minimized by locating the water flow computer at one of the centrally located dams with the largest number of generators.

II.

PLANT INTERFACE

It must be realized that it is always a grey area as to where specifications stop and design takes over. In the writing of this report it was also a grey area as to where to stop short of covering the automation of all small hydro plants, both new and retrofitted.

In using these specifications it will be necessary not only to edit the material available here but also add specifications covering plant specific items not considered here for each control device. As a specific but very important point it must be realized that the addition of a single lengthy control wire or metal conduit may breach the transient protection afforded by separate batteries and fiber optic cables.

III.

CONNECTION TO DISTRIBUTION LINE

From an economic viewpoint it is clear it will often be necessary to tie small hydro generation of less than approximately one megawatt into the nearest distribution circuit; a distribution circuit being one which normally extends radially from a substation where the input voltage may typically be 69 kV. The distribution voltage is most typically 12 kV but may range higher or lower.

In the past, the possibility of generation backfeed from a customer has been viewed as a problem of safety to personnel and equipment and therefore, not to be permitted. The problem of safety to equipment and personnel remains and must be properly solved, but now, under the requirements of the Public Utilities Regulations Procedures Act paralleling must be viewed as a requirement which the utilities must meet. (Ref. 12).

The concern arises in the event a breaker at the substation opens leaving the small parallel generation feeding some combination of loads and possibly a fault. The purchasing utility must be assured that the small generation facility will also properly detect the fault and trip free and stay free until the reclosing sequence is over. If the substation breaker did not trip due to a fault, there is concern as to the frequency and voltage which could come from the parallel generator and whether this could damage utility customers' equipment. In addition, there is concern as to whether small generators could be energized with personnel working on the line with

resultant injury.

With a synchronous generator, it is clear a voltage will be produced independent of the size or nature of any remaining load after the substation breaker opens. The frequency and voltage will surely go to a point of energy balance and this may well be far enough from 60 Hz to damage equipment before the speed control and voltage regulator can make corrections.

Induction generators will maintain an output voltage if tied to sufficient capacitive load or to a synchronous motor of proper size. The frequency and voltage will be established by energy balance until brought into tolerance by controls.

There is no evidence of standardization of requirements by the purchasing utility on the seller of small generation and, as expected, great variation exists. While quite verbose, the present specifications are generally lacking in specifics required for engineering design.

FREQUENCY TOLERANCE

The frequency tolerance and related time delay were made variable since local conditions could make a wider tolerance than the proposed +0.5 Hz necessary. For example, in rural areas, companies may form isolated islands due to network disturbances. The frequencies of the island may go outside +0.5 Hz limits and it may be desirable to keep

all possible generation on line during such an occurrence.

On the other hand, companies serving large metropolitan areas would experience excursions beyond +0.1 Hz only during extreme emergencies. Therefore, from an operating viewpoint it might be desirable to use a 0.1 Hz limit so as to immediately trip all small generation in an emergency leaving only those units on line which are under the operators complete control.

VOLTAGE TOLERANCE

The voltage tolerance was suggested at 0.1 p.u. since this is the maximum tolerance allowable a vast majority of under state statutes for industrial or residential use as far as was determined by a review conducted in 1975. Narrower limits may be necessary in many installations. The time was made variable because of variations in reclosing practice.

Most utilities first reclose a circuit within a second or so following a fault and find that power is restored a large percentage of the time. It is important that this fastest reclosing time be known and that the parallel generator tripping time on voltage, frequency or wave shape excursions be made shorter.

The utility will undoubtedly not be willing to rely on the protective equipment located with the hydro generator and should sense line voltage and reclose only into a dead line. Since one line may be

faulted, it is necessary to sense voltage on all three phases. In this way neither the utility nor the parallel generator facility are dependent on the other for safe operation.

Some utilities make a second and perhaps a third automatic attempt to close a breaker, with times up to a minute. It is important that the longest reclosing cycle be known and the parallel generation reconnection time be made longer. The generator, of course, must be reconnected by the synchronizing function if the machine is synchronous.

The inverse reduction of time for greater overvoltages is included to protect sensitive loads such as TV receivers.

UNBALANCE

Voltage and Current unbalance are problems that can result in damage both to the generator and customer equipment. It is beyond the scope of this paper to cover this in more detail other than to point out that the problem will usually be more severe on distribution circuits.

The owner should specify the protective relays necessary to protect the generator from damage due to unbalanced currents resulting from user unbalanced load, unbalanced voltages, or both. Individual phase voltage control may be needed, such as by use of single phase regulators on each phase.

WAVE SHAPE DISTORTION

Wave shape distortion from generators is not a major problem at present but several factors can lead to a growing problem.

(a) A growing use of phase switched loads as a result of application of the NASA patent on power factor controllers. (Ref. 12).

(b) Use of batteries to permit the generator speed to be variable together with the use of elementary switched inverters. Some of these inverters use the zero crossing to switch polarity and only deliver current when the battery voltage is higher than the load voltage. It is difficult to say what will happen when a number of such inverters are connected together but separated from the power system. It is clear; however, that the wave shape will deteriorate drastically.

In addition, there is a safety related problem of such an inverter setting on a dead line waiting for a polarity reversal. A noise voltage could trigger an output pulse from the inverter, dangerous to maintenance personnel.

The combination of sensitive tripping and automatic reconnection after the utility has reestablished normal service is based on the philosophy that the addition of small generation will then create no

safety hazards not already existing with present practice. Safety, however, requires a careful study of each installation and choices of bracketed portions of the specification.

IV.

REQUIREMENTS FOR DPU HARDWARE

PROTECTION FROM TRANSIENTS

The need is great to protect solid-state control and automation equipment from transients, the worst coming from a direct lightning stroke.

The present state-of-the-art is that the power engineering is sometimes done with disregard for the transient problem with the burden of protection (and blame for failure) falling entirely on the solid-state control engineer. These suggested specifications are based on the belief that an intelligent, cooperative systems approach involving all aspects of electrical station design will give the smallest possible probability of lightning or other transient damage.

STATION BATTERY

It is customary at substations and small generating plants to have a single battery for all essential protective relay, plant start-up or shutdown functions. However, the battery power required at small hydro plants can be small through use of hydraulic valve controls. In addition, it is contemplated that control and automation equipment can be built to these specifications which will consume only a few watts.

The customary network of battery and battery related control wires is a primary mode by which damaging transients are conducted to sensitive equipment. As a preferred systems approach to the

transient problem it is proposed that the battery wiring network be eliminated by use of fiber optic cables with separate batteries for each control device. As a specific but very important point it must be realized that the addition of a single lengthy control wire or metal conduit may breach the transient protection afforded by separate batteries and fiber optic cables.

ALTERNATE TO USE OF FIBER OPTICS CABLES.

Since hardware for isolation from transients by use of fiber optic cables and separate batteries may not be available as standard products it may be thought necessary to permit alternative approaches. It is suggested that ANSI standard C37.1-1979 be referred to as covering these alternatives.

COMMENTS ON THE CHOICE BETWEEN A MICROPROCESSOR COMPUTER (MPC) AND A PROGRAMMABLE LOGIC CONTROLLER (PLC).

In the pure and original form, a PLC replaces a number of relays and their contacts. Looking at this another way, a PLC solves a sequence of Boolean equations. These devices are in wide use and many control engineers are familiar with their use and with their programming.

More sophisticated PLC's are available with added analog processing and arithmetic capabilities. The major difference between these and an MPC is largely a matter of viewpoint in the hardware detail and in the method of programming.

One portion in the programming of a computer for hydro plant control is examination of contacts and making decisions on patterns of open and closed contacts. This is the equivalent of handling Boolean equations as in a fundamental PLC.

An important factor in choosing Pascal as the programming language is the ease of handling Boolean equations. Pascal is, therefore, the equivalent of a PLC with a very large number of added functions, and superior to any available PLC in applications such as hydro plant control where considerable ability beyond the handling of Boolean expressions is required.

BACKGROUND IN SUPPORT OF PHYSICAL STANDARDS

There are three general classes of mounting in existence today:

- (1) Draw-out case type for switchboard panel mounting following the tradition of electro-mechanical protective relays.
- (2) The 19" rack mount type following the tradition of the telephone switchboard industry.
- (3) The modern computer type in which little if any mechanical mounting standards have been established except for various "standard buses" where lack of agreement dominates.

The choice of a standard is further complicated by the desire to use the metric system with the accompanying problem that few U.S. manufacturers of this class of equipment have equipment built to the metric system.

The best approach is choice by the process of elimination, first looking at some fundamental factors stemming from the hydro plant environment.

Long reliable life is a most important factor.

High humidity is to be expected.

Where a dam is involved, an isolated control room will often be available. Due to the proximity of water a narrow temperature range from 0 degrees to 40 degrees C can be easily achieved.

Where a dam is not involved, such as may occur with newer developments for very low head stream flow, the equipment room could be an exposed building with a possible temperature range of -40 degrees to +65 degrees C. This requirement needs further study since microprocessors generally will not operate properly over this temperature range.

Low cost is an important factor. At larger power plants the control panels and equipment racks are separate and often in different rooms. Considerable economy can be realized by a single room with unified

control, automation and communications equipment. Provision for manual operation such as during start up and maintenance can be incorporated in the same equipment housing as the automation equipment.

The choice of drawout case mounting can be eliminated by several factors:

High cost of case.

High cost of mounting panel.

Lack of standardization between manufacturers.

CHOICE OF A "STANDARD BUS"

Considerable effort went into a study of the proposed "standard bus". especially the S100 and Multibus. Actually these proposed specifications describe a printed circuit board in complete detail. It was found that these two approaches to a standard duplicate each other unnecessarily. It was found that the industry has been unable to agree upon details regarding either approach let alone the elimination of one or the other.

Furthermore, there is a trend towards single board computers. Technology presently forces these to be larger than either potential

standard and there appears to be no standardization amongst the single board designs.

Memory technology is moving in the direction of support of a single board computer with provision for full memory expansion on the board, both RAM and ROM. Perhaps, one day this will reduce to a single chip rather than a single board. This direction eliminates the need for memory lines exiting the board and would make the S100 or Multibus obsolete.

It became obvious that the choice of a standard bus would restrict competition and would tend to support a standard which could be made technically obsolete.

DATA EXCHANGE WITH MICROPROCESSOR RELAY

The data from conventional protective relays will simply be contact closures, sensed by Type C devices. Microprocessor protective relays potentially will provide much more data and it may be desirable to transfer to the automation computer permanent data storage device.

Reference 11 gives a good summary of the progress in microprocessor applications to protective relaying. It makes no mention of a standard means of transmitting fault data for recording or the medium, of transmission. This lack of standards can lead to problems of compatibility and so a standard means of transmitting this data by fiber optics has been included.

The conclusion was that standardization should stop with the specification of 19" rack mount with mechanical, electrical and optical interfaces tied down to a level that would assure a successful mixture of equipment from more than one supplier.

It is visualized that in its simplest form the Maintenance Unit will be a "smart" display with CRT and keyboard. This would have the capability of receiving coded information and displaying it in a predetermined humanly readable format. It would also have the capability of entering the necessary commands via the keyboard to carry out the maintenance function.

In a more complex form, the maintenance unit would be a typical small computer which would contain the maintenance program and be capable of executing it.

If only one machine control and maintenance unit are involved, the most economical solution may be to include the maintenance program with the automation program in the control computer and use the simpler "smart" terminal for the maintenance unit.

If a number of machines are to be maintained by a single portable maintenance unit, it may be more economical for the maintenance unit to be a computer containing the maintenance program, perhaps specialized for each automatic machine control.

VI.

DPU PROGRAMS

FLOW DIAGRAMS

The operation of a typical plant is shown on 6.4.1.1. The careful construction of a detailed flow diagram is one of the better ways to establish communications between the hydro engineer, the computer hardware engineer and the programmer. These three professional groups tend to speak three different languages and a flow diagram can become an important meeting point.

It should be realized that a flow diagram can be expanded into more and more detail. In the example shown, 6.4.1.1 shows the overall operation but lacks in detail. The more detailed diagrams, on the other hand, are poor in showing the sequence at every point in the operation cycle that looks for trouble leading to shutdown and lockout. In the diagrams included here this shutdown sequence is shown only at a few points whereas it is present at all points in the cycle.

Note that several sequences are quite plant specific and have been omitted. such as:

- o Application of brakes.
- o Start up and shutdown of all plant auxiliaries.

VII.

PLANT PERIPHERAL DEVICES

It is recognized that none of the devices specified are commercially available at the time of writing these suggested specifications. The advantages of fiber optic cables is believed to be so important that such devices as specified will become available either as a result of issuance of these specifications or as a result of a more general demand for substation and power plant control.

VIII.

FIBER OPTICS AS THE INTERCONNECTION MEDIA

One of the most serious problems in the application of electronic equipment, of any kind, to the electric utility industry is the misoperation and damage that can be caused by lightning and switching surges conducted to the equipment by control and battery leads. Two approaches are specified here to eliminate this problem.

One is the usage of separate batteries charged by ac as discussed elsewhere. The other is the use of fiber optics to completely eliminate control leads as a source of transients. So long as data rates are not pushed to the limit, fiber optic technology is ready for use. Fortunately, in the electric utility industry, of which small hydro generation is a part, data rates, an order of magnitude below the state of the art limit, are more than adequate. This will permit trade-offs to yield very high reliability.

As far as the cost of fiber optic cables, one must consider the cost of the alternatives. For example, in substation control, some utilities are free of transient problems because they have used shielded and armored twisted pairs. The pair is used for the control; the shield is grounded at one end and the armor at both ends. This is an expensive installation, the cost of which whose cost is most likely to increase. The cost of a fiber cable, on the other hand, is likely to decrease as the use increases. Costs in the order of \$3 per meter are already below that of shielded, armored, twisted pair cable.

One of the large costs of a fiber optic cable is preparing the termination. Because of the labor and skill required, it seems most likely that cables will be factory terminated and available in standard lengths. It is suggested that the next longer length be used as required and the excess coiled at the ends.

An immediate choice between a radial and a daisy chain scheme is evident. These are defined as follows:

RADIAL: In this scheme, the microprocessor has a number of fiber cable terminations of several standard types; one for each device to be controlled or for each data or status input.

DAISY CHAIN: This would use a single cable from the microprocessor. Each controlled device would have a repeater and cable input and output permitting a cable to go from the first to second device, etc., until all are connected. Each end device would be polled by a code from the microprocessor and its data returned. In addition, controls could be sent by code to the desired end device by the microprocessor.

The Daisy Chain scheme has an advantage of simplicity at the microprocessor end; however, it has several serious drawbacks:

- (a) The polling of all end devices takes longer, by a factor equal to the number of devices, than the radial scheme. This could cause

a serious delay in certain types of emergency shutdown procedures, or alternatively could force high data rates with attendant increases in error rates.

(b) The cost of each end device increases since a more complex code receiver is required and since each device must function as a repeater.

(c) Single cable or repeater failures early in the chain have a very serious effect!

The Radial scheme, on the other hand, has several important advantages.

(1) The data can come from all outer devices in parallel for storage in buffers within the microprocessor assembly. These buffers can then be scanned at machine level speeds and priority program interrupt techniques used for certain changes in critical inputs.

(2) Loss of some cables would not require shutting the machine down. Some inputs may be only for the purpose of entering the PSD record. For example, it might be desirable to record a door entry but not shut the machine down if that input was lost.

The total length of cable used in the radial scheme may be greater but the number of terminations will be the same. The cost of the

added cable should be offset by savings in the costs of the outer devices.

The state of the art at the time of this writing in the spring of 1980 indicates it is best to consider only one directional optical cables. It appears that two directional cables will involve light splitting problems which may increase the cost and decrease the distance over which they can be reliably used.

It also appears that one directional cable leads to a fewer number of types of modules and greater flexibility of application. The trade off is that occasionally two cables must be run instead of one.

It appears a 25 kilobit per second rate should be used which will permit distances up to 2.5 kilometers with silica cable and up to 25 meters with less expensive plastic cable.

There is a wide selection of fiber optic material and diameters which will require considerable expertise to apply correctly. This, coupled with the art of proper termination, leads to the specification that the optical transmitter, receiver, and standard length of cable be purchased from the same vendor with written indication that the vendor has accepted responsibility for proper overall operation of these three components.

IX.

AUTOMATIC SYNCHRONIZING

Should the computer be used for synchronizing? (Ref. 14)

No for the following reasons:

(1) The synchronizing function is a real time problem requiring a sampling rate that can be calculated as follows.

A likely limit on Δf is 0.5 Hz: This is 180 degrees/second. For synchronizing a generator safely, no more than 1 degree error should be permitted in calculation. Thus the functions must be sampled 180 times per second.

This gives 5.55 ms for the following necessary calculations.

Prediction of a time before a zero phase coincidence by t ; the breaker closing time.

Generation of speed corrections from Δf information.

Generation of field corrections from ΔE information.

Checking of all safety related inputs which should abort the synchronizations.

This amount of calculation is beyond the capability of a minimum cost microcomputer.

(2) The cost of an automatic synchronizer is less than the added cost of a faster computer.

(3) In at least two instances known to the Author, the cost of an automatic synchronizer is less than the auxiliary hardware required to prepare data for use by a control computer for synchronizing.

(4) With a combination of an automatic synchronizer and a computer, the computer can be used to provide a redundant backup calculation of phase angle to prevent failure of either device resulting in a damaging accident. With the computer programmed for automatic synchronizing, a separate backup device must be provided if redundant safety is to be achieved.

In summary, programming the automatic synchronizing on the control computer adds cost with no compensating advantage.

Two papers are included in the Appendix which provide a basis for allowable limits on Δf and phase angle error in synchronizing. These unpublished papers are included since no other means of determining safe synchronizing limits is known to exist. Reference 15 serves as a basis for establishing the accuracy of these methods.

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APPENDIX B

EXCERPT FROM SUBCONTRACT NO. K-1569 SCOPE OF WORK

Subcontractor will write performance specifications for a standard modular set of controls for automation of small hydro plants.

The purpose of this subcontract is to define, in complete engineering detail, the performance specifications for equipment to completely automate the operation and protection of small hydro plants from 50 kW to 15 MW.

The specifications will avoid stating the means of implementing the performance required. Choices, such as analog vs digital microprocessor, will be left to those who later design equipment to meet these specifications.

Typical Choices to be Studied

A uniform design to fit a standard 19" rack will be most easily met by any manufacturer. Standard combinations of modules will permit meeting some variation in requirements that may be inevitable from plant to plant. Mounting can be in a commercially available low cost open rack or closed cabinet.

Costs will be estimated for the simplest set of controls for an induction and for a synchronous machine. This data will be valuable in making the choice of machine type.

Type of potential devices required.

Type and size of current transformers required. Iron cored transformers suffer from nonlinearity and "dc memory" and negate many of the advantages of modern solid state design. An alternate will be specified to eliminate this limitation in performance.

Probable Set of Modules

Synchronous Machine

1. Precise speed match before closing or reclosing breaker and load control after closing breaker. In the simplest case, the load control will be a full open limit switch on the water gate. In some cases, the gate may want to be controlled to a set point, produced either manually at the plant or by a remote control channel.
2. Voltage match before closing breaker and var control afterwards. It is visualized the output will be field current or field control voltage for larger machines. The field power control will vary with the size of machine and may be mounted separately for the larger sizes.

3. Breaker tripping function. This will trip the breaker for line faults, transformer faults, or machine faults. Also, for improper conditions of temperature, pressure, etc.
4. Breaker closing function. This will close the breaker synchronously either on start up or on reclosing after a line fault. It is assumed many machines will have a single line connection to the power network. The remote end will reclose rapidly and the plant breaker reclose after proper line voltage is sensed.
5. Shutdown event recording. It is assumed the only message out of the plant in case of shutdown is "I'm down, come fix me." It will often be economical to record the events leading to a shutdown to permit speedy repair.
6. Perhaps, as part of 5., some simple logic, sequencing, and coordination of the other functions will be required.
7. Recording of plant output, both kWh and kVAh. In simpler plants a counter of "hours on line" would be adequate. The metering would be required if billing of the plant output was required.

Induction Machines

All functions will become much simpler. An entirely different set may be required. Part of the study will be to determine which set may be required. Part of the study will be to determine which parts can be left the same without increasing the cost of controls for induction generators.

Important Questions

1. Will only a low voltage breaker be used with transfer tripping of remote breakers in the event of a transformer fault?
2. What communications out of the plant are required?
"I'm down, come fix me." Transfer trip to remote breakers.
Any others?
3. Consider opening low side breaker and closing high speed, high side grounding switch instead of transfer trip for transformer protection.
4. What type battery or other start up and shutdown power source will be used?

In making the study, assistance will be obtained from utilities, such as Idaho Power Company, who have several small hydro plants, and engineering companies.

APPENDIX C

CALCULATIONS OF CIRCUIT BREAKER CLOSING CRITERIA FOR SYNCHRONIZING A GENERATOR

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Abstract - An analysis is made of the electro-mechanical energy transient resulting from errors in phase angle and frequency at the instant of breaker closing and an analytical means of setting safe upper limits of these errors is given.

INTRODUCTION

It is well known that damage to a generator, and possibly to associated transformers, can be caused by the phase and frequency error which will always exist to some degree just as the circuit breaker is closed. This damage can range from the accumulated effects of many synchronizing and fault-induced force transients, incurred over a period of years, to a spectacular failure as a result of a single significant synchronizing error.

Considering the cost of replacement of a generator rotor or similar major component, present practice is at times remarkably imprecise. Synchronizing is often done manually by the "seat of the pants" method of minimizing the amount of building vibration caused by the synchronizing transient. A skilled operator can consistently reduce the shock to an undetectable level. The potential for human error is generally reduced by use of a relatively crude phase-sensitive relay in series with the operator "close" contact.

Similarly, automatic synchronizers are set over a wide range of phase angle and frequency difference limits as determined by the experience and opinion of a responsible person or persons. With only a few exceptions^{7,8} it is the experience of the author that available analytical methods are seldom used in setting synchronizing error limits.

Present technology can be depended on to eliminate the possibility for a catastrophic synchronizing error. It is less certain that incremental damage will always be eliminated. Extremely precise automatic synchronizers exist which are capable of reliably eliminating even incremental damage, but simple analytical criteria for their safe adjustment have not heretofore been available. Previous work has been

directed toward the power/torque transient with precise mathematical modeling of a particular machine. There is a need for a simpler mathematical model which may not be as accurate but can easily be applied to any generator. To meet this need, it must be established that the resulting equations and method of application fail in accuracy in the direction safe to the machine. This paper is proposed as a solution to this problem, or at least a start in that direction.

Background

Previous work has explored in detail those aspects of synchronizing error that are equivalent to faults. The goal was mainly to establish accurate analytical models which could be used in the design of machines to withstand faults and synchronizing errors. With a few exceptions, this analysis is not generally used to calculate limit settings for automatic synchronizers.

The previous work develops a detailed analysis of forces produced by current buildup, in turn caused by a phase difference across the synchronizing breaker at the instant it closed. Frequency difference is assumed to be zero and the effects of a frequency error with no phase error at the instant of closing appear not to have been analyzed.

Previous analyses consider the torques set up by faults or synchronizing errors but do not directly consider the energy involved. This analysis will consider the energy balance of the rotating machine and the system to which it is being connected.

THE SYNCHRONIZING ENERGY TRANSIENT

Consider a system consisting of an ideal generator connected by an impedance to a generator whose size approaches infinity. The ideal generator will have a single impedance and neither the generator nor the interconnecting impedance will have losses. It is clear that an energy transient can be defined for such a system and that the energy transient for a real system with losses can be no greater.

Figure 1 is the simplified electrical model to be used. Figure 2 describes the energy transient which will oscillate between the machine rotor and the interconnected system.

The transient oscillation can be explained in detail by following the sequence of four conditions 90° apart, as in Figure 2. Starting at 0°, a positive phase angle, as defined here, delivers power to the infinite bus.

Figure 1. Simplified Network

Figure 2. Transient Diagram

At 90° , this power flow from the machine has reduced the electrical phase angle to zero and has produced an underspeed in the rotor equivalent to $\Delta\omega$ radians per second electrically or $\Delta\omega/N$ radians per second of shaft rotation.

At 180° , the underspeed reduces again to zero and results in a negative phase angle of maximum power flow back to the finite machine.

At 270° , the power flow into the machine has again reduced the phase angle to zero resulting in an overspeed of $\Delta\omega$ electrically or $\Delta\omega/N$ mechanically. The process then repeats.

A standard fault is proposed which can be used as a base for the energy transient produced by any machine disturbance whether it be a fault, a switching operation or synchronizing. The proposed definition follows:

A one per unit fault is a three phase fault on a fully loaded generator which produces no change in generator rotor position with respect to the expected no fault position.

The fault energy for a standard fault is then:

$$\epsilon_f = P_g \Delta t_f \text{ joules}$$

The stored energy in the rotor is:

$$\epsilon_r = P_g H' \text{ joules}$$

where:

$$H' = \frac{H}{P_g}$$

The fault energy in per unit with the stored energy in the rotor as a base is:

$$D_f = \frac{\Delta t_f}{H'} \quad (A)$$

While machines are designed to withstand faults, one does not fault machines on purpose. Synchronizing, on the other hand, is planned and necessary. It seems wise, therefore, to choose a value of D_s small in comparison with D_f , such as 10%.

Comments must be made about the use of H , above. The inertial constant H is normally defined as stored rotational energy divided by machine rating in KVA. This results in H having the dimensions of wattseconds per volt-ampere. For the purpose of this paper, it is assumed that the machine rating in watts is used so that H' has the dimension of seconds. It is then easy to interpret H' as the number of seconds of rated prime mover input which equals the stored energy in the rotor.

CALCULATION OF AUTOMATIC SYNCHRONIZER SETTINGS

Data Required

H' the machine inertial constant in seconds.

x_t the sum of the machine transient impedance, transformer impedance and line impedance in per unit.

Δt_f the expected fault clearing time at the generator in seconds.

Procedure

Calculate:

$$D_f = \Delta t_f / H' \text{ from equation (A)}$$

a dimensionless per unit number.

Using additional equations derived in the appendix:

Choose a safe D_s less than D_f .

Calculate:

$$\Delta f_s = 30 D_s \quad (11)$$

maximum allowable slip rate in hertz.

Calculate:

$$\delta_s^\circ = 787 D_s (H' x_t)^{\frac{1}{2}} \quad (12)$$

maximum allowable closing angle error in degrees.

Out of general interest, the fundamental resonant frequency of the generator and interconnected system is:

$$\alpha' = 2.185 \left(\frac{1}{H' x_t} \right)^{\frac{1}{2}} \quad (13)$$

resonant frequency in hertz.

Typical Calculation

Assume the following:

$$H' = 3 \text{ seconds}$$

$$\frac{x''}{x'} = 0.2$$

$$\frac{x'}{x} = 0.3$$

$$\frac{x}{x_n} = 1.5$$

$$\frac{x_n}{x_t} = 0.2 \text{ (transformer plus network)}$$

$$\Delta t_f = 0.05 \text{ seconds}$$

We obtain for a 60 Hz system; assuming $D_B = 0.1 D_f$:

$$\Delta f_s = 0.05 \text{ Hz from equation (11)}$$

$$\delta_s^0 = 1.61^\circ \text{ from equation (12)}$$

$$\alpha' = 1.99 \text{ Hz from equation (13)}$$

Comments on Procedures

Note the following in the application of these procedures:

- (1) It is assumed no difference in rms voltage magnitude exists across the open breaker. If small differences did exist, the principal result would be the flow of reactive current which, in turn, would not contribute to the energy transient.
- (2) A problem will arise in deciding what machine impedance to use in the above procedure. In many instances, the machine impedance will be swamped out by the transformer and network impedance so that the choice will make little difference as compared to other judgement decisions, such as the ratio of D_B to D_f .

The equations derived here have been used with the data from Reference [6] and compared to the first cycle of each curve of Figure 5 from that paper. The result was sufficiently accurate to support use of the simple equations derived here for the intended purpose of setting limits for generator synchronizing. Best results were obtained using the subsynchronous reactance. It is, therefore, suggested that the subsynchronous reactance be used in applying the equations derived in this paper.

- (3) It is assumed that the electrical angle θ measured across an open synchronizing breaker is equal to the rotor angle δ with respect to the infinite machine as a reference. The symbol δ is, therefore, used in the analysis to represent θ just before the breaker is closed or δ just after the breaker is closed.

Sources of Error

In applying the results, several errors must be considered:

- (1) Maximum phase angle error of an automatic synchronizer, if used.
- (2) Tolerance in breaker closing time. Note that an automatic synchronizer will compensate for the expected breaker closing time. The actual closing time will vary with temperature, age and other factors by at least ± 0.2 of the expected closing time. This will cause a closing phase angle error of:

$$\delta_e = 360 \Delta f_B \Delta t_b$$

- (3) Error in synchroscope and worst case human error, if manual synchronizing is used. Note that frictional error of a rotating synchroscope may be several degrees, even when rotating very slowly.

The sum of the phase angle errors must be no greater than the calculated safe limit, since the transient from Δf and the one from δ_s add in accordance with equation (2), and since it must be assumed that synchronizing can occur with worst case values of both Δf and δ_s , then the resulting power transient will be greater by $(2)^{\frac{1}{2}}$ times either one alone.

Note, in any system containing two generators, that for synchronizing transients a virtual infinite machine exists at some point in the network between the machines. If the machines are identical, the virtual point exists at the symmetrical midpoint of the network.

CONCLUSIONS

By using energy equations, simple criteria for setting phase angle and frequency difference for synchronizing have been established. In addition to the simplicity, the equations generated here relate the frequency difference and phase angle errors. Previous work handled the phase error in more detail and probably with greater accuracy. The results were useful for machine design but did not immediately lead to a safe setting of synchronizing phase angle error. As far as has been determined, past work did not approach the problem of frequency error.

APPENDIX

In the derivation, note that real quantities are first used and per unit quantities substituted before the final results are obtained. Where a quantity is used both in its real and per unit form, the per unit form is underlined>.

List of Symbols

- α = resonant frequency, radians per second
- α' = resonant frequency in hertz
- Δf_s = maximum allowable slip rate in hertz
- $\Delta \omega$ = slip rate, radians per second
- $\Delta \omega_s$ = maximum allowable $\Delta \omega$
- δ = generator phase angle in radians
- δ_e = phase error caused by tolerance in breaker closing time

δ_s = maximum allowable δ at instant of synchronizing in radians
 δ_s^o = maximum allowable δ at instant of synchronizing in degrees
 $\epsilon_{\Delta\omega}$ = component of ϵ_s "stored" as $\Delta\omega$
 $\epsilon_{\Delta\omega_s}$ = maximum value of $\epsilon_{\Delta\omega}$
 ϵ_δ = component of ϵ_s "stored" in phase angle
 ϵ_{δ_s} = maximum value of ϵ_δ
 ϵ_r = stored energy in rotor in wattseconds (joules)
 ϵ_s = synchronizing transient energy in wattseconds (joules)
 H = machine inertial constant in kW sec/kVA
 H' = machine inertial factor in seconds
 ω = electrical frequency, radians per second
 B = per unit uncertainty in t_b
 D = per unit transient energy with machine inertial stored energy as base
 D_f = per unit transient from fault
 D_s = value of D used as safe criteria for synchronizing
 e_g = machine line to neutral potential in volts
 f = electrical frequency in hertz
 I_m = rated maximum phase current in amperes
 ℓ = machine rotor inertia in watt seconds³
 N = number of pole pairs
 PF = rated power factor
 P_g = generator rating in watts
 ω_s = rotational speed in radians per second
 Δt_b = expected breaker closing time
 Δt_f = normal time in seconds for nearby fault to be cleared
 x_g = generator reactive impedance
 x_n = network reactive impedance
 x_t = impedance per phase from generator internal voltage to infinite bus in ohms

Derivations

By the law of conservation of energy there will be a constant differential of energy between a simple lossless mechanical oscillating system and the same system at rest. The finite generator and its electrical "shaft" connecting it to the infinite machine form a simple torsional pendulum in which the differential energy oscillates at a resonant frequency between storage as potential energy of instantaneous maximum phase angle and storage as relative torsional velocity of motion. Figure 2 describes this oscillation as the product of the constant scalar magnitude of the energy and a unit vector rotating in the phase angle - frequency difference plane at the resonant frequency. Figure 2 and the derivations of equations are for the safe limit value of the energy transient.

Since: $s = \frac{\omega}{N}$

$$\epsilon_s \ll \epsilon_r$$

$$\Delta\omega_s \ll \omega$$

then:

$$\epsilon_{\Delta\omega_s} = \frac{1}{2} \ell \left(\frac{\omega + \Delta\omega_s}{N} \right)^2 - \frac{1}{2} \ell \left(\frac{\omega}{N} \right)^2$$

$$\epsilon_{\Delta\omega_s} = \frac{\ell \omega \Delta\omega_s}{N^2} \quad (1)$$

$$\epsilon_s = \left(\epsilon_{\delta_s}^2 + \epsilon_{\Delta\omega_s}^2 \right)^{\frac{1}{2}} \quad (2)$$

The phase angle δ which will produce a maximum frequency difference, $\Delta\omega_s$, is found by:

$$\delta = \delta_s \cos \alpha t$$

at any point in time: $\frac{d\delta}{dt} = \Delta\omega$

$$\left. \frac{d\delta}{dt} \right|_{\alpha t = \frac{\pi}{2\alpha}} = \Delta\omega_s = \alpha \delta_s$$

$$\delta_s = \frac{\Delta\omega_s}{\alpha} \quad (3)$$

D is defined as:

$$D = \frac{\epsilon_s}{\epsilon_r}$$

Using (1) and (2) at $\delta = 0$

$$D = \frac{\ell \omega \Delta\omega_s}{N^2} \cdot \frac{2N^2}{\ell \omega^2}$$

$$\Delta\omega_s = \frac{D\omega}{2} \quad (4)$$

Combining (3) and (4)

$$\alpha = \frac{D\omega}{2\delta_s} \quad (5)$$

The energy received from the infinite machine in converting the potential energy represented by δ_s at $\alpha t = 0$ to dynamic energy of $\Delta\omega_s$ at $\alpha t = \pi/2\alpha$ is found by using the power flow equation:

$$\text{Power} = \frac{3E_g^2 \sin \delta}{x_t}$$

Integrating from $\alpha = 0$ to $\alpha = \frac{\pi}{2\alpha}$ and recognizing that at small angles $\delta = \sin \delta$, the value of ϵ_{δ_s} is determined:

$$\epsilon_{\delta_s} = \frac{3E_g^2 \delta_s}{x_t \alpha}$$

Combining with equation (1)

$$\delta_s = \frac{l\omega\Delta\omega_s \alpha x_t}{3 E_g^2 N^2} \quad (6)$$

From (4), (5) and (6)

$$\delta_s^2 = \frac{l\omega D^2 \omega^2 x_t}{12 E_g^2 N^2} \quad (7)$$

$$H' = \frac{\frac{1}{2} l \left(\frac{\omega}{N} \right)^2}{3 E_g I_m} = \frac{l\omega^2}{6 N^2 E_g I_m}$$

$$l = \frac{6 H' N^2 E_g I_m}{\omega^2} \quad (8)$$

Combining (7), (8) and converting to x_t :

$$\delta_s = D \left(\frac{\omega H' x_t}{2} \right)^{\frac{1}{2}} \quad (9)$$

Combining (5) and (9)

$$\alpha = \frac{D\omega}{2} \cdot \frac{1}{D} \left(\frac{2}{\omega H' x_t} \right)^{\frac{1}{2}} = \left(\frac{\omega}{2 H' x_t} \right)^{\frac{1}{2}} \quad (10)$$

Putting (4), (9), and (10) into a more easily used form with electrical phase angle in degrees and frequency of 60 Hz:

$$\Delta f_s = 30 D \quad \begin{array}{l} \text{max allowable} \\ \text{slip rate in} \\ \text{hertz} \end{array} \quad (11)$$

$$\delta_s^{\circ} = 787 D \left(H' x_t \right)^{\frac{1}{2}} \quad \begin{array}{l} \text{max} \\ \text{allowable} \\ \text{closing (12)} \\ \text{angle in} \\ \text{degrees} \end{array}$$

$$\alpha' = 2.185 \left(\frac{1}{H' x_t} \right)^{\frac{1}{2}} \quad \begin{array}{l} \text{resonant} \\ \text{frequency (13)} \\ \text{in hertz} \end{array}$$

Note that in equation (10), only x_t is a per unit quantity. This can be converted to a pure per unit equation, with time base of one second, by substituting the following identities:

$$\omega = 120 \pi \omega_b \quad \text{and} \quad \alpha = 120 \pi \omega_n$$

where ω_b is one radian per second, base and ω_n is per unit resonant frequency,

$$H' = \frac{m_t}{240 \pi}$$

where m_t is per unit inertia, equation (10) then becomes:

$$\omega_n = \left(\frac{\omega_b}{x_t m_t} \right)^{\frac{1}{2}} \quad (14)$$

This agrees with Wood's¹⁸ equation (7) except that he uses x''_d . His term for reactance does not seem appropriate here, since it is the sum of the time varying machine reactance and the fixed transformer and system reactance.

REFERENCES

- [1] M. S. Baldwin and J. J. Bonk, "Some New Considerations in Generating Unit Protection," American Power Conference, Chicago, Illinois, April 17-20, 1977.
- [2] M. S. Baldwin and R. H. Daugherty, "Transmission Line Switching and its Effect on Generators," Missouri Valley Electric Association, Kansas City, Missouri, April 13-15, 1977.
- [3] J. W. Batcheler, D. L. Whitehead, J. S. Williams, "Transient Shaft Torques in Turbine Generators Produced by Transmission-Line Reclosing," AIEE Transactions, Vol. 67, Part I, pp 159-165, 1948.
- [4] P. G. Brown, "Transmission Line Reclosing-Turbine Generator Duties and Stability Considerations," Conference for Protective Relay Engineers, College Station, Texas, April 12-14, 1976.
- [5] M. Canay, "Stresses in Turbogenerator Sets Due to Electrical Disturbances," Brown, Boveri & Company, Ltd., Baden, Switzerland, Publication No. CH-T 070 153 E.
- [6] R. D. Dunlop and A. C. Parikh, "Verification of Synchronous Machine Modeling in Stability Studies: Comparative Tests of Digital and Physical Scale Model Power System Simulations," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No. 2 March/April 1979.

- [7] W. B. Gish, B. D. Hamann and D. W. Chamot, Eds., Synchronizing Hydroelectric Generators with Minicomputers. Bureau of Reclamation, Division of General Research, Denver, January 1974.
- [8] W. B. Gish and S. C. Still, Eds., Speed and Voltage Matching with Control Channel Delay - Grand Coulee PMSC Synchronizing Algorithms. Bureau of Reclamation, Division of General Research, Denver, January 1976.
- [9] J. S. Joyce, T. Kulig and D. Lambrecht "Torsional Fatigue of Turbine - Generator Shafts Caused by Different Electrical System Faults and Switching Operations." IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, pp 1965-1977, Sept./Oct., 1978.
- [10] E. W. Kimbark, Ed., Power System Stability: Synchronous Machines. New York: Dover Publications, Inc., 1968.
- [11] H. S. Kirschbaum, "Transient Electrical Torques of Turbine Generators During Short Circuits and Synchronizing." AIEE Transactions, vol. 64, pp 65-70, February 1945.
- [12] H. E. Lokay, C. Raczkowski and D. G. Ramey, "Turbine - Generator Mechanical Requirements Due to Power System Interactions." American Power Conference, Chicago, Illinois, April 17-20, 1977.
- [13] W. W. Parker, H. A. Travers, "Reclosing of Single Tie Lines Between Systems." AIEE Transactions, vol. 63, pp 119-122, March 1944.
- [14] R. Quay and R. J. Placek, "Cyclic Fatigue of Turbine - Generator Shafts." IEEE Winter Power Meeting and Tesla Symposium, 1976.
- [15] V. W. Ruskin, "Maximum Short Circuit and Faulty Synchronizing Torques on Generator Foundations." AIEE Transaction on Apparatus and Systems, vol. PAS-74, Part III, pp 618-624, August 1955.
- [16] J. B. Tice and P. G. Brown, "Circuit Breaker Reclosing-Stability and System Considerations." Pennsylvania Electric Association Relay Committee Fall Meeting, Stroudsburg, Pennsylvania, October 4-5, 1973.
- [17] E. C. Whitney and H. E. Criner, "Determination of Short-Circuit Torques in Turbine Generators by Test." AIEE Transactions, Vol. 59, pp 885-889 and 1195-1197, 1940.
- [18] A. J. Wood, "Synchronizing Out of Phase." AIEE Transaction on Apparatus and Systems, vol. PAS-76, Part III, pp 1-10, April 1957.

APPENDIX D

COMPARISON OF PAPERS

"CALCULATIONS OF CIRCUIT BREAKER CLOSING
CRITERIA FOR SYNCHRONIZING A GENERATOR"

ROBERT W. BECKWITH

AND

"VERIFICATION OF SYNCHRONOUS MACHINE MODELING IN STABILITY STUDIES:
COMPARATIVE TESTS OF DIGITAL AND PHYSICAL SCALE MODEL POWER SYSTEM
SIMULATIONS."

R. D. DUNLOP AND A. C. PARIKH

BY

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OCTOBER, 1979

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The literature is nearly void of data comparing real world measured data with machine/network mathematical models. One notable exception is the paper by Dunlop and Parikh listed as reference 6 of the Beckwith paper.

A comparison of the simple equations of the Beckwith paper with the results of Dunlop and Parikh are presented here in draft form. The draft assumes the reader has a copy of the Dunlop/Parikh paper at hand. Note that this is found in a recent (1979) volume of "IEEE Transactions on Power Apparatus & Systems." Comments will be appreciated and will be incorporated in a final version of this comparison paper.

First, let us consider some fundamentals:

Phenomena found on an electric power network can be divided by frequency into three categories which have a degree of independence but not complete independence from each other.

- (1) Those phenomena generally falling an order of magnitude or greater above the power frequency and not harmonically related to it. The relationships between single and three phases often is unimportant to this phenomenon.
- (2) Those phenomena related to the power frequency, its harmonics, and a small band about each of these to provide for amplitude and phase changes in the fundamental or its harmonics.

Note that the reactive or "imaginary power" flow does involve the flow of real power, however, it flows between places of storage within the network

and the energy involved is not lost to the system.

In a single phase circuit real power may flow past a point on a lossless network which involves exchange of energy stored as charge on a capacitor to the same energy stored as magnetic field in an inductance. The exchange of energy in a lossless system consisting of a single inductance and capacitance can be represented by the product of the constant value of the stored energy and a unit vector rotating at the resonant frequency. The axes are voltage and current.

The energy, ϵ_C , stored as charge on the capacitor by voltage, E , at the instant the current equals zero is a function of the size of the capacitor, C , and is equal to:

$$\epsilon_C = \frac{1}{2}CE^2$$

The energy, ϵ_L , stored as magnetic flux by current I at the instant the voltage is zero is a function of the size of the inductance, L , and is equal to:

$$\epsilon_L = \frac{1}{2}LI^2$$

In a lossless system, obviously $\epsilon_C = \epsilon_L$

The resonant frequency is, of course:

$$\omega (LC)^{-\frac{1}{2}}$$

In a lossless balanced three phase system, reactive power may flow in each of the three phase conductors, however the sum of the three is at all times zero. Reactive power, therefore, does not flow even momentarily past a point on a three phase system but rather rotates between phases on either side of the point. The total stored energy on one side must equal that stored on the other side. Note that energy of this category can only be stored as charge on a capacitor or field of an inductance and cannot involve machine inertia.

Note also that in a completely stable and non-changing power network with both real and reactive power, that the resonant frequency of the reactive storage elements must precisely equal the power frequency. In power terms, we say that for stability the system must be adjusted to balance the flow of reactive power (stability here meaning non-varying). In circuit terms, we would say the system has been adjusted for resonance at the system frequency.

- 3) Those phenomena related to frequencies well below the fundamental power frequency which involve the movement of rotating machine masses relative to each other. In this category, the machine inertias constitute the only means of energy storage and the flow of reactive, category (2), power and storage of the related energy is not involved.

We can define reactive power flow in this category (3) of phenomenon as that required to transfer inertial energy from one machine to another. This transfer of energy will be by means of real power flow at the system

frequency. In other words, real power flow in Category (2) can constitute reactive power flow as defined for Category (3). It is true real power in Category (2) since, for example, it may involve the flow of energy for several cycles in or out of a given machine. In terms of the overall network, however, the energy does not leave the network and may therefore be properly described as reactive relative to Category (3).

This is analogous to observing that within a cycle at the power frequency, real unidirectional power flows from one Category (2), storage device to another.

A general definition of reactive power could be that it involves the movement of energy within a network under the restriction that at the end of one cycle of a frequency of interest, the energy balance is the same as at the start of the cycle.

If the finite and infinite machine used in my analysis were coupled by a shaft and the machines driven by prime movers, then the phenomena of Category (3) used in my analysis would be entirely independent of the electrical network (since it would not exist). Instead, the phenomena of Category (3) are 'coupled' to the phenomena of Category (2) by the generator windings and the interconnecting transmission line.

I use the energy which flows by means of Category (2) phenomena over a quarter cycle of the resonant frequency α of Category (3) to measure the

reactive energy flow of Category (3) (which I call the synchronizing energy transient).

Note that there surely is a change in inertial energy as the instantaneous speed of the finite rotor changes from $\omega + \Delta\omega$ to $\omega - \Delta\omega$. The total change in energy is twice that which I calculate. The energy $\epsilon_{\Delta\omega}$ is the change in inertial energy between a condition of phase displacement at frequency ω and a condition of zero phase displacement at either speed $\omega + \Delta\omega$ or $\omega - \Delta\omega$ (please excuse my equating frequency to shaft speed, but only the number of poles is involved in any difference between the two). Surely, it is both intuitively as well as mathematically clear that the difference in energy for a given value of $\Delta\omega$ is a function of the total inertia of the finite machine. The energy difference related to a $\Delta\omega$ for a very large machine could easily be equal to the total inertial energy of a small machine. The energy difference cannot possibly be independent of the inertia.

Real power at system frequency ω will flow in one direction for a half cycle at frequency α starting with maximum $\Delta\omega$ and ending with minimum $\Delta\omega$. An equal amount of power will then flow the other direction. The time integral of this power flow will equal the total change in inertial energy. The time integral over 90° is obviously half that over 180° and therefore equal to half the total change in inertial energy as desired for my derivation.

Let me approach the argument somewhat differently:

- (a) The power which flows is a function of angle δ and impedance x_t but not a function of inertia.
- (b) Energy is the time integral of power. The longer the time, the greater the energy.
- (c) The resonant frequency of Category (3) phenomena is given by my equation (10) which agrees with Woods' equation. These show α is a function of inertia. Therefore, the time of integration and resulting energy are functions of inertia.

Now we can proceed with a comparison of the Beckwith and the Dunlop/Parikh paper:

This comparison was made using Figures 5 and 6 of the AEP paper which most nearly corresponds to the synchronizing situation. The results are given in Table I. The following explains each column.

α' scaled: This was determined by counting the cycles of the MIT machine for a time, generally 3 seconds, and dividing by the time.

α' computed: This was computed using equations (13) and using:

$$\underline{x_t} = -\sqrt{(X_d'')^2 + (X_g'')^2} + X_e = 0.550$$

δ_{MIT} scaled: This was scaled as the change in angle from the start of each curve to the first peak

δ_s : This was computed from equation (12) using:

$$D = \frac{P_g \cdot \Delta t \cdot PF}{60 H'}$$

where $\Delta t =$ cycles breaker was open

Δf_s scaled: This was scaled from the curves from the first negative slope.

It should be noted it is very difficult to do this with any accuracy.

Δf_s scaled: This was scaled from the curves from the first negative slope. It should be noted it is very difficult to do this with any accuracy.

Δf_s : This was computed from equation (11)

$\Delta \delta$ initial: This is the angle change while the breaker is open, computed from:

$$\Delta \delta = \int_0^{\Delta t} \Delta \omega dt = \frac{\omega (\Delta t)^2}{4H'}$$

Δf initial: This is the frequency change while the breaker is open, computed from:

$$\frac{\Delta t}{H'} = \frac{2\Delta\omega}{\omega}$$

$$\Delta\omega = \frac{\omega\Delta t}{2H'}$$

$$\Delta f = \frac{\omega\Delta t}{4\pi H'}$$

Comparison of the scaled and computed angle shows an error which increases with increase in the initial angle at time of reclosing the breaker. Additional transient energy is added since the initial power will be more than the 0.9 or 0.3 when the breaker opened. If this could be computed and added to D, a closer comparison of initial peak angle would result.

This is merely a problem of comparing two similar but unlike situations. The first three curves with initial angles of 7.2° are most like synchronizing and give reasonably good results.

If the MIT machine model is correct and the analytical model incorrect, then the data shows the fault transient is a strong function of reactive current level and direction just prior to the fault. This involves category 2 stored energy which I did not get into in my paper. With a close in 3 phase fault, the sum of the inertia!

prime mover, and reactively stored energy must be dissipated within the machine and transformer. The stored electrical energy at the end of the fault must be taken into account in some manner. Fortunately, the inertial energies are simple to calculate based on fundamentals in which one has considerable confidence.

From Table III, it is easy to compute the prime mover input as 0.3 or 0.9 per unit. From this and energy equations it should be possible to compute X_d . From the change in backward swing correlated to reactive power, it may be possible to compute a value for X_g . I could be wrong about this, but it seems worth taking a look at the technique.

A standard fault is proposed which can be used as a base for the energy transient produced by any machine disturbance whether it be a fault, a switching operation or synchronizing. The proposed definition follows:

A one per unit fault is a three phase fault on a fully loaded generator which produces no change in generator rotor position with respect to the expected no fault position.

The fault energy for a standard fault is then:

$$\epsilon_f = P_g \Delta t_f \text{ joules}$$

The stored energy in the rotor is:

$$\epsilon_r = P_g H' \text{ joules}$$

Where:

$$H' = \frac{H}{PF}$$

The fault energy in per unit with the stored energy in the rotor as a base is:

$$D_f = \frac{\Delta t_f}{H'} \quad (1)$$

For the MIT machine of the AEP paper:

$\Delta f = 0.53$ Hz for a 5 cycle fault with the machine fully loaded

$$\Delta \delta = \frac{P_g}{g} \int_0^{\Delta t_f} \Delta \omega dt = \frac{P_g \omega (\Delta t_f)^2}{4H'} \quad \text{radians}$$

and $\Delta \delta = 8^\circ$

This is the most $\Delta \delta$ and Δf can advance in 5 cycles from full prime mover input.

The angle and frequency can drop due to braking action of the fault, however,

If the angle swing backward 8° , it is clear that the fault transient is double the per unit fault transient D_f which I suggested might be approximated by $\Delta t_f / H'$.

If the rotor angle did not change during a fault (in accordance with AEP calculations) then my value for D_f would be correct. In other words, the entire prime mover input went into fault energy and none into changing the inertial stored energy.

If the rotor swing backwards, then the fault energy is the sum of the prime mover input and the loss of inertial energy. These are both easy to calculate.

Calculations regarding a generator with one P. U. load which is unloaded for a short time, Δt : assuming a 2 pole machine.

$$\epsilon_r = \frac{1}{2} J \omega^2 \quad \text{rotor inertial energy at normal speed}$$

$$\epsilon'_r = \frac{1}{2} J (\omega + \Delta\omega)^2 \quad \text{inertial energy with } \Delta\omega \text{ change in frequency}$$

$$D_f = \frac{\frac{1}{2} J (\omega^2 + 2\Delta\omega\omega + \Delta\omega^2) - \frac{1}{2} J \omega^2}{\frac{1}{2} J \omega^2} \quad \text{Per unit change in stored energy due to } \Delta\omega$$

$$\approx \frac{2\Delta\omega}{\omega} \quad \text{for } \Delta\omega \ll \omega$$

$$\frac{\Delta t}{H'} = \quad \text{per unit change in prime mover output energy assuming all went into rotor inertial energy during time } \Delta t$$

$$\frac{\Delta t P}{H'} = \frac{2\Delta\omega}{\omega} \quad \Delta\omega = \frac{P_g \omega \Delta t}{2H'}$$

Δt and H' in seconds; $\Delta\omega$ and ω in radians / sec

The equations derived here have been used with the data from reference (AEP Paper) and compared to the first cycle of each curve of Figure 5 from that paper. The result was sufficiently accurate to support use of the simple equations derived here for the intended purpose of setting limits for generator synchronizing. Best results were obtained using the subsynchronous reactance. In fact, the machine impedance can be determined from data in this reference by working back through equation (13). It is, therefore, suggested that the subsynchronous reactance be used in applying the equations derived in this paper.

The results of the comparison are tabulated in Table 1.

- The first column refers to the Dunlop/Parikh paper.
- The second column is the resonant frequency, scaled from the Dunlop/Parikh paper.
- The third column contains the resonant frequencies calculated per the Beckwith paper.
- The fourth column is the peak phase angle as scaled from the Dunlop/Parikh paper.

- The fifth column is the value of D calculated from the data scaled from the Dunlop/Parikh paper and then used in the calculations from the Beckwith paper.
- The sixth column is the value of allowable phase angle at instant of breaker closing as calculated from the Beckwith paper.
- The seventh column is the maximum frequency increase as scaled from the MIT machine data.
- The eighth column is the value of Δf_s computed from the equations of the Beckwith paper.
- The ninth column is the phase angle at instant of breaker closing as scaled from the Dunlop/Parikh paper.
- The last column is the frequency difference at instant of breaker closing as scaled from the Dunlop/Parikh paper.

A study of Table I shows reasonably good agreement between columns 4 and 6 and between 7 and 8 for Figures 5 - 1 through 5 - 6 of the Dunlop/Parikh paper.

Differences can easily have resulted from the great difficulty in scaling these data from the published figures in the Dunlop/Parikh paper. In the case of Figures 6 - 1 and 6 - 2 the angles are so great that assumptions used in the Beckwith paper are not valid; for example $\sin X = X$ is hardly true at angles of 99° or 84.3° . The point is, it is not expected that the equations of the Beckwith paper will ever yield angles so great that $\sin X = X$ is not a reasonably valid assumption.

It is believed that this comparison indicates the equations of the Beckwith paper are sufficiently accurate for the intended purpose of establishing safe criteria for synchronizing.

Figure	α' scaled	α' Computed	δ_{MIT} Scaled	D	δ_s computed	Δf_s Scaled	Δf_s Computed	$\Delta\delta$ Initial Degrees	Δf Initial Hz
5-1	1.67	1.35	18.3	.016	20.2	.37	.45	7.2	.24
5-2	1.57	"	18.9	.016	20.2	.44	.45	7.2	.24
5-3	1.53	"	18.1	.016	20.2	.41	.45	7.2	.24
5-4	1.73	"	17.0	.0106	13.4	.41	.3	9.6	.16
5-5	1.43	"	17.2	.0106	13.4	.40	.3	9.6	.16
5-6	1.37	"	17.0	.0106	13.4	.45	.3	9.6	.16
6-1	1.36	"	99.0	.0415	52.5	1.58	1.23	48.5	.62
6-2	1.23	"	84.3	.0266	33.7	1.55	.8	59.8	.40

TABLE 1.

IV. ABBREVIATIONS USED

CRT - Cathode Ray Tube
DPU - Digital Processing Unit
MMI - Man/Machine Interface
MPC - Microprocessor Computer
PDSD - Permanent Data Storage Device
PLC - Programmable Logic Controller
PPS - Program Performance Specifications
p.u. - per unit quantity
RAM - Random Access Memory
ROM - Read Only Memory
RPD - Resistive Potential Device
VAR - Volt-Ampere, Reactive

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V. GLOSSARY

baud - a unit of signalling speed equal to the number of discrete conditions or signal events per second.

call routine - a high level routine which calls subroutines and is used as the main sequencing program.

checksum - some combination of the "1"s in a binary sequence used for checking.

data lines - the communications lines, modems, and communication controls of all stations connected to the line, used in the transmission of information between two or more stations.

discrete - specific, finite.

dump - either manual or DPU controlled: to copy all or part of the contents of stored information from the DPU to the PDSD.

firmware - an electrically readable device in which a program is stored, which does not require power to maintain and which cannot be modified while in the DPU.

flicker - a low frequency voltage variation which is disturbing when used for lighting.

format - the general order in which information appears on the input media.

machine code - an operation code that a specific machine is designed to recognize.

major trouble - a problem requiring immediate breaker tripping.

minor trouble - a problem which permits normal shutdown to lockout.

non-volital memory - one which does not depend on power to be maintained.

Pascal - the name of a high level programming language.

P-code - pseudo code: See Reference 4.

port - a place of access in a device where power can be supplied or withdrawn or where variables can be observed and measured.

storage media - a diskette or tape that stores data not alterable by computer instructions.

VI. REFERENCES

A very large number of references were used in writing this report. These consisted of DOE reports, manufacturers' brochures, technical papers, magazines, and textbooks. Only the most important and hard to find references are listed below.

STANDARDS:

ANSI/IEEE C37.90a-1974, Guide for Surge Withstand Capability (SWC) Tests (Supplement to ANSI/IEEE C37.90-1978).

ANSI/IEEE C37.2-1979, Electrical Power System Device Function Numbers.

ANSI C83.9-1972, Racks, Panels, and Associated Equipments.

ANSI X3.1-1969, Synchronous Signaling Rate for Data Transmission.

ANSI X3.12-1970, Vocabulary for Information Processing.

ANSI X3.24-1968, Signal Quality at Interface Between Data Processing Terminal Equipment and Synchronous Data Communication Equipment for Serial Data Transmission.

ANSI X3.4-1977, Code for Information Interchange.

ANSI X3.5-1970, Flowchart Symbols and Their Usage in Information Processing.

ANSI Y10.5-1968, Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering.

ANSI Y14.15-1966 (R1973), Electrical and Electronic Diagrams, including Supplements Y14.15a-1970 (R1973) and Y14.15b-1973.

ANSI/IEEE Std 91-1973, Graphic Symbols for Logic Diagrams (Two-State Devices).

ANSI/IEEE Std 200-1975, Reference Designations for Electrical and Electronic Parts and Equipments.

ANSI/IEEE Std 315-1975, Graphic Symbols for Electrical and Electronic Diagrams.

EIA Std RS-232-C, Interface Between Data Terminal Equipment and Data Communication Equipment Employing Serial Binary Data Interchange (August 1969).

EIA Std RS-363, Standard for Specifying Signal Quality for TRansmitting and Receiving Data Processing Terminal Equipment Using Serial Data Transmission at the Interface with Nonsynchronous Data Communication Equipment (May 1969).

EIA Std RS-404, Standard for Start-Stop Signal Quality Between Data Terminal Equipment and Nonsynchronous Data Communication Equipment (March 1973).

ANSI/NEMA ICS6-1978, Enclosures for Industrial Controls and Systems.

Mil Std 1472B, Human Engineering.

IBM General Information Manual GA27-3093-0

ANSI/ISO/TC 97/SC 5 N 510 - Programming Languages (Feb 19, 1980); available in IEEE COMPUTER SOCIETY TUTORIAL INTRODUCTION TO PASCAL, Prepared by A. Windsor Brown, March 1980, pg. R-41; also available in PASCAL NEWS Number 18 Communications about the Programming Language Pascal by Pascalers, May 1980, pg. 69.

IEEE Task 696.1/D2 Standard Specification for S-100 Bus Interface Devices.

Intel AP-28 Multibus Interfacing Application Note.

OTHERS:

- (1) U. S. Army Corps of Engineers. Ft. Belvoir, VA. The Hydrologic Engineering Center, Davis CA. NATIONAL HYDROELECTRIC POWER RESOURCES STUDY, Vol. 5: Southeast Region, July 1979.
- (2) "Energy Outlook 1980-2000", Exxon Public Affairs Dept., P. O. Box 2180, Houston, TX 77001.
- (3) Howard A. Mayor, Jr., Charles W. Smith, SMALL HYDRO CONTROL AND OPERATION, for Small Scale Hydro Power Feasibility, Planning and Design, University of Idaho, 1979, Allis-Chalmers, Hydro-Turbine Division, York, PA .
- (4) W. H. Wattenburg, SUMMARY OF THE DISSERTATION SUBMITTED IN PARTIAL SATISFACTION OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY. University of California, Graduate Division, Northern Section, January 1961.
- (5) Jack Hemenway, Edward Teja (eds.), "Pascal Update". ELECTRONIC DESIGN NEWS, April 5, 1980, pg. 100-105.
- (6) A. Windsor Brown, IEEE COMPUTER SOCIETY CHAPTER TUTORIAL INTRODUCTION TO PASCAL, March 1980.
- (7) Dale A. Viskoe, "Fiber Optics Provide 500-kV Substation Control Link", TRANSMISSION & DISTRIBUTION, March 1980, pg. 72-78.
- (8) Stephen Ohr, Sid Adlerstein, "Fiber Optics Is Growing Strong-Better Connectors. Cables Will Speed Things Up", ELECTRONIC DESIGN, VOLUME 27, 23, Nov 8, 1979.
- (9) T. Takagi, et al., "Development of an Intrastation Optical-Fiber Data Transmission System for Electric Power Systems", IEEE TRANSACTIONS ON POWER APPARATUS AND SYSTEMS, Vol. PAS-99, No. 1, January/February 1980.
- (10) K. Tanaka, et al., "Application of Microprocessors to the Control and Protection System at Substation", IEEE TRANSACTION ON POWER APPARATUS AND SYSTEMS, Vol. PAS-99, No. 1, January/February 1980.
- (11) "Computer Relaying", IEEE Tutorial Course Text, #79 EH0148-7-PWR.
- (12) Public Utility Regulatory Policies Act of 1978, P.L.95-617, 92.
- (13) U. S. Letters Patent 4,052,648, National Aeronautics and Space Administration.
- (14) D. R. Bjork, et al., DIGITAL SYNCHRONIZER FOR COMPUTER CONTROLLED GENERATING STATIONS, Montana State University, Montana Power Company.

(15) R. D. Dunlop, A. C. Parikh, "Verifications of Synchronous Machine Modeling in Stability Studies: Comparative Tests of Digital and Physical Scale Model Power System Simulations", IEEE TRANSACTIONS ON POWER APPARATUS AND SYSTEMS, Vol. PAS-98, No. 2, March/April 1979.