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CONTENTS

AUXILIARY POWER SYSTEM FOR THE DIABLO CANYON NUCLEAR PLANT

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ABSTRACT

This paper describes the auxiliary electric power system for the Diablo Canyon Nuclear Plant of the Pacific Gas and Electric Company. The power systems covered are the medium and low voltage distribution systems, the standby and startup systems, and the emergency and engineered safety features systems. Also covered are the selection of voltages, methods of neutral grounding, and automatic transfer to standby power. A discussion is also included for the systems with the largest loads: the main condenser cooling water system and the reactor coolant system.

INTRODUCTION

The Pacific Gas and Electric Company is currently building a large nuclear power plant at the Diablo Canyon site. The site is on the Pacific Coast in San Luis Obispo County, California. The plant will have two large generating units; the estimated electrical output rating is 1084 mW for Unit 1 and 1106 mW for Unit 2. The units have pressurized water reactors and 1800 rpm single shaft turbine generators. The generators are hydrogen cooled and have water cooled stators and brushless rotating rectifier type excitation systems. The general plant layout is shown in Figure 1.

The plant electric power systems consist of the output from the main generator and an auxiliary power system composed of 12,000, 4,160 and low voltage systems of 480 volts and 120/208 volts. All of the auxiliary power systems buses can be fed from either the main generating unit or from the standby-startup off-site power source. The emergency power system can also be supplied by engine-generators.

AUXILIARY ELECTRIC POWER SYSTEMS

The plant auxiliary loads are supplied by the auxiliary power system shown by the single line diagram in Figure 2. Some of the loads are large and required a new approach to the system design.

Medium and Low Voltage Power Systems

The 12,000 volt system has two buses per unit, each bus with one 13,000 hp condenser circulating water pump and two 6,000 hp reactor coolant pumps. The switchgear is of the indoor metaclad type with vertical lift circuit breakers rated 13.8 kV, 80,000 asymmetrical amperes momentary and 750 mVA interrupting capacity.

The 4,160 volt system has five buses, two that serve balance of plant equipment and three that serve the nuclear engineered safety features and other emergency loads. The latter three buses are also each served by an engine-driven generator. The switchgear is also of the same type, and is rated 4.16 kV, 80,000 asymmetrical amperes momentary and 250 mVA interrupting capacity.

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The engineered safety features and other emergency services are fed from three 4,160 volt buses, each supplied by an engine generator as well as the normal off-site and main unit power sources. Nuclear safety-related loads have been grouped to meet single failure criteria. The low voltage engineered safety features and emergency services are fed radially and independently from their corresponding 4,160 volt bus through a transformer coupled to a motor control center.

Standby and Startup Power System

The standby-startup system serves as a source of electric power both for startup and for standby during normal operation. It consists of two outdoor, oil filled, three phase transformers, rated 45/60/75 mVA OA/FOA/FOA, each fed at 230 kV from the off-site power source and serving two 12,000 volt buses, one for each unit. These two 12,000 volt buses are connected together by a circuit breaker that is normally operated open. In case of trouble in one transformer, this breaker can be closed manually to restore off-site power to the affected unit through the other transformer. Standby-startup power is fed to the 4,160 volt and low voltage systems through a transformer supplied from the 12,000 volt system.

Unit Auxiliary Power System

The main generating unit supplies power at 25,000 volts to the auxiliary power system through two transformers, one to 12,000 volts and the other to 4,160 volts. The power transformers are outdoor, oil filled, three phase units; the one serving the 12,000 volt system is a two winding delta-delta unit rated 33.75/45/56.25 mVA OA/FA/FA, and the one serving the 4,160 volt system is a three winding (two 4,160 volt windings) delta-wye unit, rated 24/32/40 mVA OA/FA/FA. These same transformers can supply the auxiliary power from the 500 kV system when the main generating unit is out of service by opening a disconnect switch in the generator isolated phase bus and re-energizing the main transformer. This disconnect switch is manually controlled from the main control room.

Normal Operation

During normal steady-state operation, the main generating unit is operated on the "unit" principle, supplying all of its own auxiliary power. While it is operating normally, the main generating unit is considered its own best power source, and is less vulnerable to disturbances in the off-site power sources. The standby-startup power system will be operated in a standby state, and the diesel generators will be shutdown, except if electric power system capability is degraded, the engine generators will be operated as required by IEEE Standard 308.

The main generating unit auxiliaries will be started up from the standby-startup power system. After the unit has been synchronized with the 500 kV system, the auxiliary loads will be transferred manually, one bus at a time, to the main unit by momentarily paralleling the off-site and main generator systems. Normal shutdown will use the reverse procedure.

Emergency Operation

Emergency shutdown of the main generating unit, including the reactor, will cause all of the auxiliary power systems to be transferred to the standby-startup, off-site power source, if available, and will start the diesel generators. If this source is not available, the emergency loads will be automatically transferred to the diesel generators in a sequential manner.

Emergency Power System

The emergency power systems serve loads at 4,160, 480 and 120 volts ac and at 125 volts dc.

The 4,160 volts system has been divided into three load groups to provide redundancy and to be within the capacity of the diesel generators. Two diesel generators for each unit are sufficient to carry the emergency loads that are required for safe operation under normal and accident conditions. One of the diesel generators is common to both main generating units, and is transferred automatically to the main unit which requires actuation of safety features.

Automatic transfer of the emergency loads to the off-site or diesel generator sources is initiated by either a main unit trip, an actuation signal from the reactor protection system, or from loss of 4,160 volt vital bus potential. Loads are started in a sequence with 5 second intervals to prevent inrush overload on the diesels. Each motor has an individual independent adjustable time delay relay to permit each load to act independently of the others.

With the three bus system, single failure will result in only a partial loss of redundancy, because most of the loads are of the one out of two type of redundancy. Depending on their bus supply, some will not be interrupted at all upon failure of one bus or sources. Some loads have a two out of three or a three out of five configuration and these require all three sources to meet single failure criteria.

The diesel generators are self-contained units, housed indoors at ground level in individual rooms at the end of the turbine generator building. The diesel generators have a net electrical output rating of 2,600 kW continuously and 2,750 kW for 2,000 hours per year. The generator is air cooled and is rated 3,250 kVA, 0.80 power factor, 4,160 volts, 60 hertz, three phase 70°C temperature rise. The insulation is class B and the enclosure is drip proof. The transient reactance is 14.6 percent, and the subtransient reactance is 8.4 percent. The exciter is a static series transformer type controlled by a static voltage regulator.

During the starting sequence for the safety related loads, these machines can carry the short time overloads caused by transients and starting currents and still maintain the electric power frequency within 5% and hold the voltage to a minimum of 75% and recover to 100% in one second.

The diesel engine is a heavy duty, four cycle, turbo-charged, stationary unit, rated 3,691 horsepower, 900 r/min. The engine is water cooled and has an integrally mounted radiator with an engine driven fan for cooling the engine jacket water.

Each diesel generator has two air motor starting systems, and is capable of reach rated voltage and speed within 10 seconds. With one air motor operative, this time is 12 seconds.

Control, Protection and Instrumentation Electrical Systems

The 125 volt dc system has been divided into three groups for each unit to match the divisions of the emergency ac system. Each group consists of a set of 125 volt battery chargers and switchgear. Spare chargers are provided, with two of the buses sharing one spare charger, and the third bus has its own spare. Each charger is fully capable of carrying the maximum load on its bus as well as providing recharging of the battery should it have been discharged. The batteries have the capacity to supply their loads for the duration required even without allowance for the diesels immediately relieving some of the load. Two pairs of batteries are coupled between the two units to provide 240 volts dc for lubricating oil pumps.

Nuclear instrument and protection systems which require ac power are fed from electric power inverters, one for each protection channel, for a total of four. These inverters will automatically derive their power from either the batteries or the diesel-generators, without any switching. Although there are four such systems, only three are required to meet the single failure criteria and also to prevent an erroneous safety action from the failure of a single instrument. The inverters are arranged on the buses so that they match the three bus schemes of the ac and dc vital power systems.

Neutral Grounding

The neutrals of the auxiliary electric power systems are high resistance grounded. The maximum power expended in the resistors has been made equal to the capacitive current flowing when one phase is grounded. This minimizes the transient voltages caused by arcing grounds and at the same time limits damage caused by current flow. On the 12 kV system, the maximum current will be limited to 35 amperes, and on the 4,160 volt system, the current is held to 7 amperes. The grounding resistors are of the high voltage type, and are installed in the secondary side of the standby-startup and the unit auxiliary transformers. The 12,000 volt system uses a zig-zag transformer as a grounding bank.

Ground faults for each motor and transformer is detected and alarmed. Ground tripping is not used so that service can be maintained until the equipment can be removed from service with less disturbance to the power system.

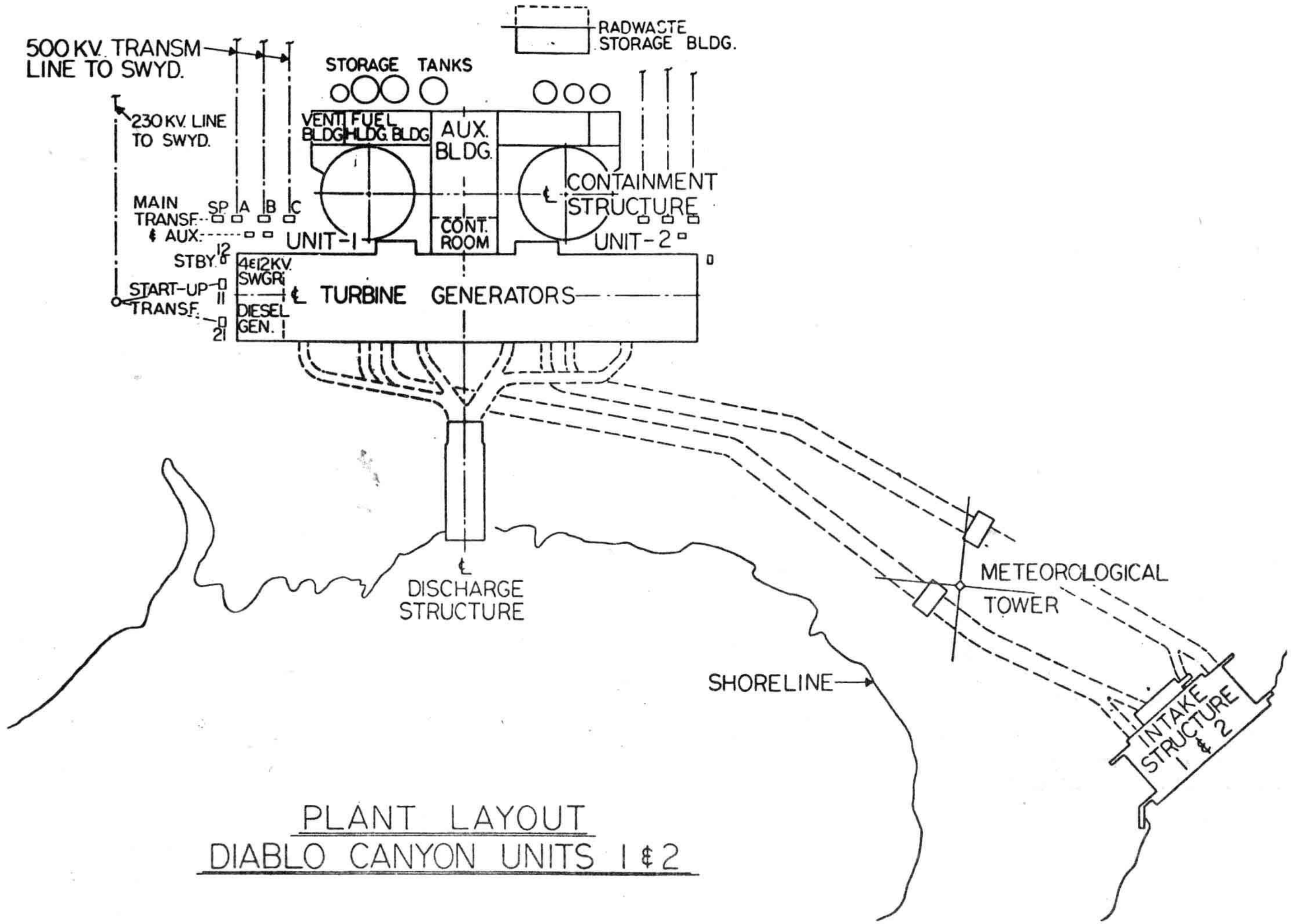
Voltage Ratings of Large Motors

The large motors required for this project made it necessary to use an operating voltage higher than has been usually used in our power plants. We decided to use standard metalclad switchgear, to start the motor directly across the line, and to limit voltage drop on motor starting to 15%. With the 13,000 horsepower motors, this requires a voltage between 11,500 to 13,800 volts because of the limitations of interrupting ratings standard lower voltage metalclad switchgear. 11,500 volts was selected because it is within the rating range for normal operation of 13.8 kV switchgear and yet it required the minimum increase in physical size and cost of the reactor coolant pumps.

Automatic Transfer of Auxiliary Loads

Our normal practice is to delay transfer of electric motors until their residual voltage has decayed to 25% of rated value before reclosing. This practice eliminates any need for concern for the phase angle between the voltages of the source and the motor during reclosing. This angle is a function of the initial phase angle difference and the deceleration of the motor during its power interruptions and above 25% residual voltage this angle should be below 60° to avoid excessive stresses on the motors upon reclosure. Because three factors are difficult to foresee and control, we have adopted the voltage decay method even though it may cause more disturbances to the loads.

There is one exception – the reactor coolant pumps. To cause the least upset to the reactor coolant flow, the reactor coolant pumps will be transferred with a minimum of power interruption, only the time required to close one circuit breaker upon the trip of the other, or about 0.15 second. The reactor coolant pumps have flywheels to raise the total inertia to 3,455 kilogram-meter^2, resulting in a H inertia constant of 4.92 kW-sec/kVA. This makes it possible to make a fast transfer and as well as to provide adequate reactor coolant flow on coastdown following a prolonged power failure. Figure 3 shows 25° during a 0.15 second interval of no power. Figure 3 is based on typical induction motor characteristics and load torque that varies as the square of the speed, typical of centrifugal loads such as used here. The equations for Figure 3 were derived by analytic mechanics from the fundamental laws of motion and show that the retard angle is a function of the H inertia factor and load torque in per unit values.



PLANT LAYOUT
DIABLO CANYON UNITS 1 & 2

Figure 1

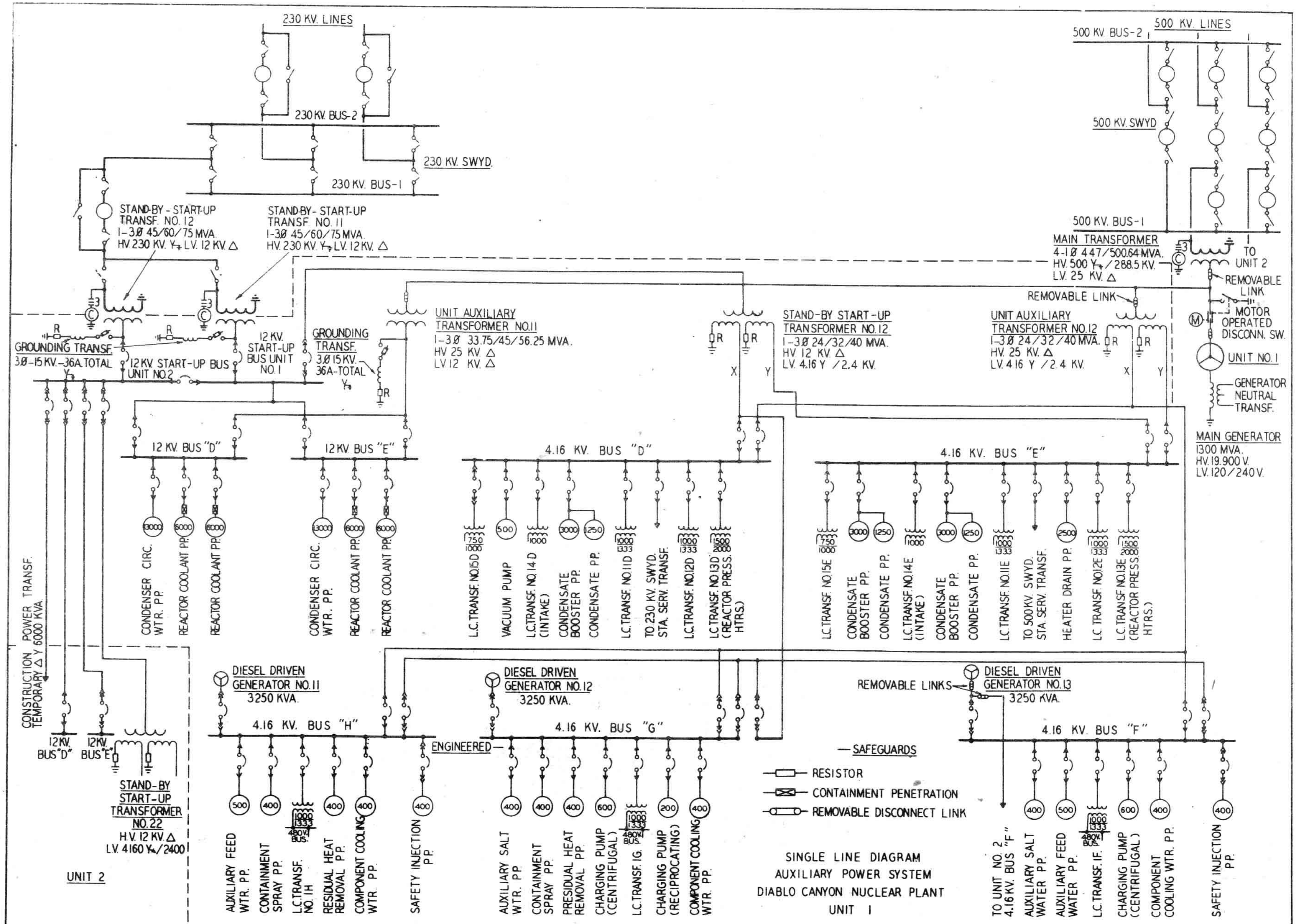

230 KV. LINES
230 KV. BUS-2
230 KV. SWYD.
230 KV. BUS-1
STAND-BY - START-UP TRANSF. NO. 12 1-3Ø 45/60/75 MVA. HV 230 KV. Y LV. 12 KV Δ
STAND-BY - START-UP TRANSF. NO. 11 1-3Ø 45/60/75 MVA. HV 230 KV. Y LV. 12 KV. Δ
GROUNDING TRANSF. 3Ø-15 KV.-36A TOTAL
12 KV. START-UP BUS UNIT NO. 2
12 KV. START-UP BUS UNIT NO. 1
GROUNDING TRANSF. 3Ø 15 KV. 36A-TOTAL
UNIT AUXILIARY TRANSFORMER NO. 11 1-3Ø 33.75/45/56.25 MVA. HV 25 KV Δ LV 12 KV. Δ
STAND-BY START-UP TRANSFORMER NO. 12 1-3Ø 24/32/40 MVA. HV 12 KV Δ LV. 4.16 Y /2.4 KV.
UNIT AUXILIARY TRANSFORMER NO. 12 1-3Ø 24/32/40 MVA. HV. 25 KV. Δ LV. 4.16 Y /2.4 KV.
500 KV. LINES
500 KV. BUS-2
500 KV. SWYD.
500 KV. BUS-1
MAIN TRANSFORMER 4-1Ø 447/500.64 MVA. HV. 500 Y /288.5 KV. LV. 25 KV. Δ
TO UNIT 2
REMOVABLE LINK
REMOVABLE LINK
MOTOR OPERATED DISCONN. SW.
UNIT NO. 1
GENERATOR NEUTRAL TRANSF.
MAIN GENERATOR 1300 MVA. HV. 19.900 V. LV. 120/240 V.
12 KV. BUS "D"
12 KV. BUS "E"
CONDENSER CIRC. WTR. PP.
REACTOR COOLANT PP.
REACTOR COOLANT PP.
CONDENSER CIRC. WTR. PP.
REACTOR COOLANT PP.
REACTOR COOLANT PP.
4.16 KV. BUS "D"
L.C. TRANSF. NO. 15D
VACUUM PUMP
L.C. TRANSF. NO. 14 D (INTAKE)
CONDENSATE BOOSTER PP.
CONDENSATE PP.
L.C. TRANSF. NO. 11D
TO 230 KV. SWYD. STA. SERV. TRANSF.
L.C. TRANSF. NO. 12D
L.C. TRANSF. NO. 13D (REACTOR PRESS. HTRS.)
4.16 KV. BUS "E"
L.C. TRANSF. NO. 15E
CONDENSATE BOOSTER PP.
CONDENSATE PP.
L.C. TRANSF. NO. 14E (INTAKE)
CONDENSATE BOOSTER PP.
CONDENSATE PP.
L.C. TRANSF. NO. 11E
TO 500 KV. SWYD. STA. SERV. TRANSF.
HEATER DRAIN PP.
L.C. TRANSF. NO. 12E
L.C. TRANSF. NO. 13E (REACTOR PRESS. HTRS.)
CONSTRUCTION POWER TRANSF. TEMPORARY Δ Y 6000 KVA
12 KV. BUS "D"
12 KV. BUS "E"
STAND-BY START-UP TRANSFORMER NO. 22 H.V. 12 KV Δ L.V. 4160 Y/2400
UNIT 2
DIESEL DRIVEN GENERATOR NO. 11 3250 KVA.
4.16 KV. BUS "H"
AUXILIARY FEED WTR. PP.
CONTAINMENT SPRAY PP.
L.C. TRANSF. NO. 1H
480V. BUS.
RESIDUAL HEAT REMOVAL PP.
COMPONENT COOLING WTR. PP.
SAFETY INJECTION PP.
ENGINEERED
DIESEL DRIVEN GENERATOR NO. 12 3250 KVA.
4.16 KV. BUS "G"
AUXILIARY SALT WTR. PP.
CONTAINMENT SPRAY PP.
PRESIDUAL HEAT REMOVAL PP.
CHARGING PUMP (CENTRIFUGAL)
L.C. TRANSF. IG.
480V. BUS.
CHARGING PUMP (RECIPROCATING)
COMPONENT COOLING WTR. PP.
SAFEGUARDS
RESISTOR
CONTAINMENT PENETRATION
REMOVABLE DISCONNECT LINK
SINGLE LINE DIAGRAM
AUXILIARY POWER SYSTEM
DIABLO CANYON NUCLEAR PLANT
UNIT 1
REMOVABLE LINKS
DIESEL DRIVEN GENERATOR NO. 13 3250 KVA.
4.16 KV. BUS "F"
TO UNIT NO. 2 4.16 KV. BUS "F"
AUXILIARY SALT WATER PP.
AUXILIARY FEED WATER PP.
L.C. TRANSF. IF.
480V. BUS.
CHARGING PUMP (CENTRIFUGAL)
COMPONENT COOLING WTR. PP.
SAFETY INJECTION PP.

Figure 2

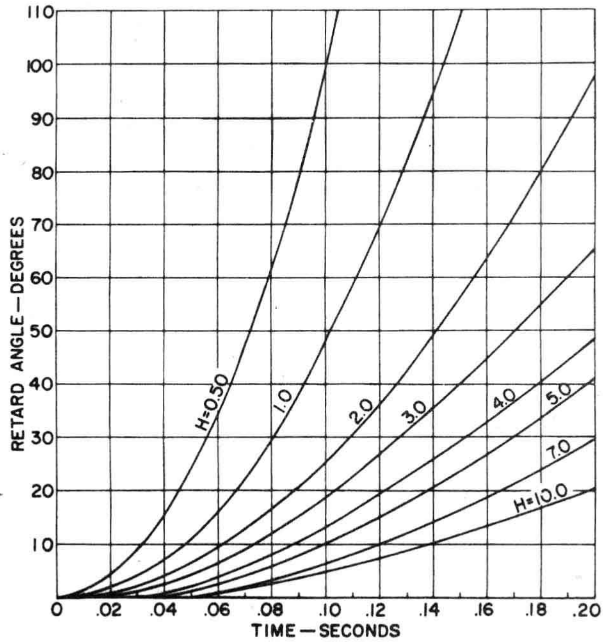


Figure 3

On the other hand, the condenser circulating water pumps and motors have a total inertia of 65,950 kilogram-meter^2, but because of their size and speed, the H inertia constant is only 1.57, much lower than that of the reactor coolant pumps. Because the motors are large and slow, it would be uneconomical and impractical to raise the inertia of these pumps by adding mass to get more flywheel effect. With this lower inertia, the phase will retard about 85° and this can cause excessive inrush currents. Therefore, these motors have transfer delayed until the residual voltage drops to 25%. This interval is a function of the open circuit time constant of the motor, about 0.654 second in this case. The speeds of the pump during coastdown are shown in Figure 4, which shows that the motor speed will still be above 80% of rated speed during the time interval of 0.80 second, to reach 25% speed, enough to make recovery to normal speeds easily. Figure 4 is based on the same factors as for Figure 3.

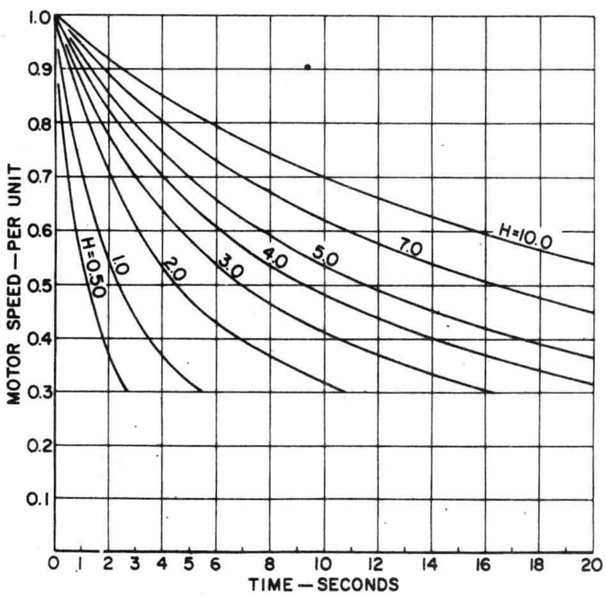


Figure 4

Lastly, a brief description of the two systems with the largest electric motors and, therefore, with great influence on the design of the auxiliary power system follow:

Condenser Cooling Water System

Because this plant has a ground elevation 85 feet above sea level and a large amount of sea water, 54,690 liters per second (867,000 gallons per minute) is needed to cool the main condenser, the power required for the circulating water pumps is 26,000 horsepower for each unit. Two pumps are used for each unit, each driven by a 13,000 horsepower, 3.96 r/s (237.7 r/min.) vertical shaft, water cooled squirrel cage induction motor, the largest of this kind in service. These motors are rated 11,500 volts and have a power factor of about 81%. The rotor of the motor has a diameter of 3.83 meters, a thickness of 1.21 meters, and has a mass of 32,886 kilograms. The rotor and pump impeller are direct coupled, and are supported by the motor thrust bearing of self-aligning sliding-shoe Kingsbury type immersed in oil cooled by water.

These motors can withstand a speed of 5.25 r/s (315 r/min.), the maximum runaway speed in reverse while water is draining from the conduits after a shutdown.

These motors are squirrel-cage induction-type and are started directly across the line start without any need to dewater the pump. However, starting is prevented while the rotor is running in reverse above speeds of 5 r/min. to prevent an excessive starting period. From a standstill, these motors reach full speed in only 8 seconds. Starting current inrush is about 5 times the rated value.

Synchronous and induction motors were evaluated for this application. The induction motors were selected based on lower original cost, comparable efficiency, and simpler starting and reclosure characteristics. The cost of these motors were also a factor considered in the evaluation of the elevation of the plant.

At this time, the condenser cooling water is returned to the sea through a series of energy dissipating cascades in the discharge structure. Originally, hydro-generation was considered for this purpose. But, at that time – in the late nineteen-sixtees – the costs were unfavorable. Also, the prevention of corrosion of the hydraulic turbine and its related chambers when exposed continuously to sea water became very costly and difficult to achieve. However, with the increase in value of energy and the advancement of techniques to prevent corrosion, we are again evaluating the use of a hydro-generator at Diablo to recover some of the energy, about 12,500 kW per unit, from the falling condenser cooling water.

Reactor Coolant System

The reactor coolant system provides reactor core cooling adequate at all times to maintain a margin against boiling, or a DNBR of 1.3 or greater. The flow is provided by four reactor coolant pumps, designed to pump high temperature (about 300°C average) reactor coolant in large volumes (5,580 liters per second for each pump) at high pressure (2,250 pounds per square inch absolute). The pumps require 5,449 horsepower when the coolant is hot, and 7,241 horsepower when it is cold.

The pumps are driven by squirrel cage induction motors, of the air cooled, vertical shaft type, rated 6,000 horsepower, 19.7 r/s (1,180 r/min.). The insulation is class B. Atop each motor is a steel flywheel, 1.91 meters in diameter and 0.33 meters thick, with a mass of 5,820 kilograms.

The motors have segmented pad type radial bearings and Kingsburg type thrust bearings. The motors have ratchets to prevent reverse rotation should one be shutdown while the others are running.

The motor can withstand an overspeed of 125%. To reduce overspeed and to maintain coolant flow for a short time following a reactor or turbine tup, the reactor coolant pumps, the main generator and the transmission system remain connected for 30 seconds before the generator is tripped off the line.