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THE LATEST CONTROL SYSTEM OF HYDRO-ELECTRIC POWER STATIONS

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I. INTRODUCTION

In response to increased power demands, many thermal-electric and hydro-electric power stations have been built. The recent tendency, in the development of power plants, has been to build "thermal" first and "hydro" second, as it seems that sites for the establishment of large output hydro-electric plants are rarely to be found. However, the hydro-electric power station possesses many superior features in its control and operation, i.e, easy starting, quick response to a load variation, economical operation, etc., to the contrary, compared with a "thermal" power station where problems arise in the cost and period of time necessary for erection.

We wish to describe the latest control systems which may be used in connection with the operational methods found in generating plants.

II. OPERATION OF A HYDRO-ELECTRIC GENERATING PLANT

Many pre-war manually operated power stations still remain in operation. The machinery, imported from foreign countries, is almost all manually operated. However, present generating plants, with the exception of small plants, are being constructed to operate automatically. By definition, an automatic plant is one that may be operated and controlled by one man with all the controls located at a central switchboard. The decision by the previous Japan Electric Power Generation and Transmission Company to adopt standard systems has contributed considerably to the development of the automatic plant. Each equipment manufacturer in Japan has done his utmost to further the development of various kinds of machines and apparatus along the lines of the standard system. It is presumed that the supervisory control system and AFC of the power stations concerned could be operated by one man. For each individual control device, new control systems and new ideas have been or are now being adopted for their use in the operation of a generating plant.

It must be realized that as periodic variations in power demands occur in certain areas, these demands will be accommodated by the total power increase from several generators located in several plants rather than by only one generator in one plant. A variation in power demand is detected as a change in frequency, Δf. A variation of power flow in the tie line is detected as a power change, ΔP. By combining these variations, various kinds of controls such as FFC, TBC, FTC, etc., may be carried out. When many power stations are controlled, the controlling instructions must be dispatched from a single station, otherwise various stations will take various actions on the detected values, thereby causing unnecessary power exchanges to be made which in turn may induce a useless power loss in the area. To accomplish this, supervisory controlling equipment must be provided to keep in contact with distant stations. When such controls are used, the power station selected will ordinarily be a dam system large capacity hydro-electric type. Special consideration must be given when controlling many hydro-electric stations, connected in series, so as to make it possible to utilize this important power resource most effectively. In addition, transmission line losses and various machine and apparatus efficiencies must be taken into account as well as the relationship between "thermal" and "hydro" power plants. In order to control many power stations in a highly efficient manner we must rely upon the indispensable aid of ELD, i. e. the Economic Load Dispatching Computer. To initiate progressive stages of control in a hydro-electric power station the following steps must be followed: (1) Each power station should be automatic or at least capable of perfect one man control. (2) Supervisory control eqiupment should be provided to connect the central supply command office to each power station. (3) The central command office should contain a highly efficient and centralized AFC device and an ELD. Digital systems are considered as an excellent means to keep in contact with distant stations both from the point of accuracy and signalling reliability. Because of the high state of accuracy necessary in detection and calculation by AFC and ELD, the problem has become too difficult to be handled by an analog computer. In view of the above, our company has endeavored to develop machines and apparatus for use in this field by new power stations and other plants. More than 60% of the machines and apparatus that have been supplied by us for use in hydro-electric power stations have been equipped with supervisory controlling and telemetering equipment in some form: 50% of these have been supplied with equipment which can co-ordinate commands from a central dispatcher. This equipment is a non-contact type of system in that semi-conductors and transistors have been fully utilized. As an example of this, a hydro-electric power station has been introduced here where a mother power station has been equipped with a transistorized power line carrier telecontrol-telemeter so that her intake gates may be controlled from the daughter power station (*Fig. 1*). *Fig. 2* and *Fig. 3* show other examples where a digital computer has been provided as the main piece of control equipment, thereby providing the means for highly reliable control. AFC and ELD devices are mainly used to control effective power needed in a system; however, the modern tendency has been to use digital devices to also control var-power.

III. CONTROL DEVICE AT POWER STATION

The source of energy at hydro-electric power stations is dependent upon water conditions; therefore, system operating changes are often necessary. Various adjustments are carried out by such controls as a water level governor upstream of the power station and a water flow governor or a reservoir water level governor downstream.

1. Water Level Governor

The control system is of an integrating type; i. e. if the level is regulated by only a water level detector, an external disturbance on the pond causes a variation in the flow quantity; therefore, in order to eliminate the stationary deviation caused by the above disturbance, the governor must possess integrating characteristics in the stationary domains. To accomplish this, there are two standard systems: sampled data control and continuous control.

1) Sampled data control system

This system is utilized by power stations that have

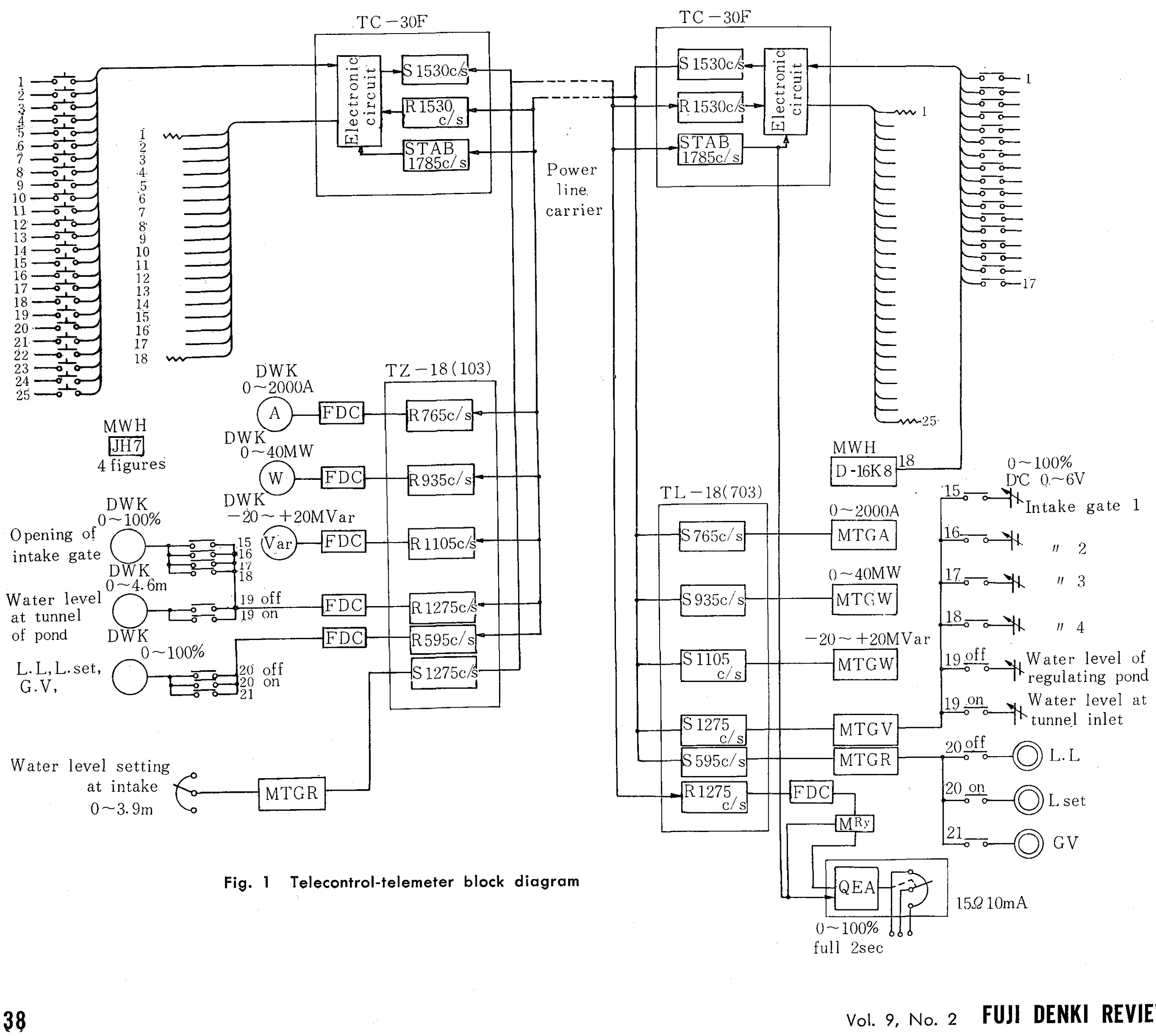
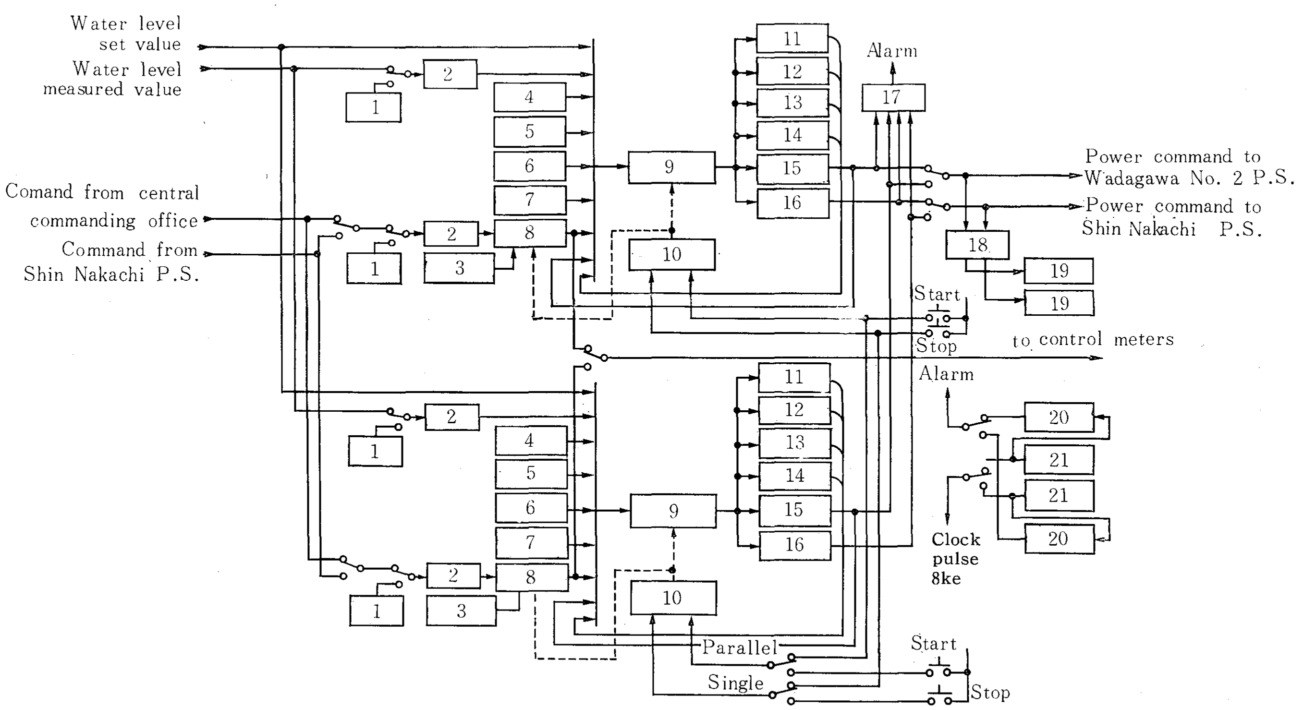


Fig. 1 Telecontrol-telemeter block diagram



① For testing
② Memory
③ Power flow speed
④ Proportion sensibility
⑤ Integrating time
⑥ Differential time
⑦ Distribution factor of Wadagawa No. 2 P.S.
⑧ Lagging circuit
⑨ Calculation circuit
⑩ Control circuit
⑪ Temporary memory
⑫ Integral value memory
⑬ Differential value memory
⑭ Compensated value memory
⑮ Wadagawa No. 2 P.S. power memory
⑯ Shin-nakachi P.S. Power memory
⑰ Check
⑱ Binary decimal/decimal
⑲ Indication
⑳ Clock pulse checking
㉑ Clock pulse generating

Fig. 2 Block diagram of digital computer part for parallel control

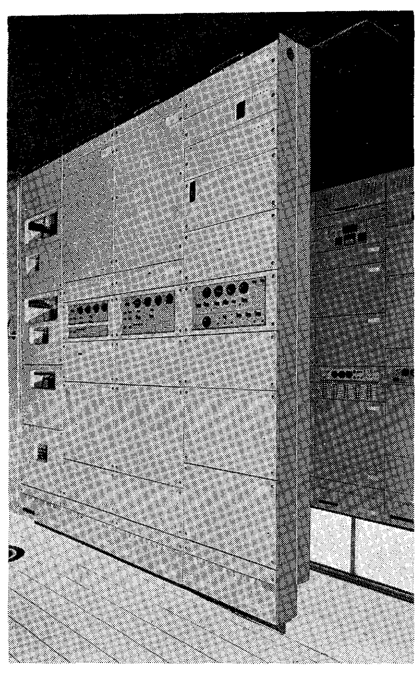


Fig. 3 Transistorized telecontrol device

comparatively large reservoirs or are located where sudden water flow variations do not occur. The outstanding features of this system are:

(1) The operating device is an insulated contact type, making power delivery to the governor motor extremely easy.

(2) The detection section becomes simple since the bridge relay input may be made very small and upon insertion of an adapter, such as a function generator, special control operations may be performed. (Examples of various applications will be explained later.) An explanatory diagram is shown in *Fig. 4*.

Explanation of the various components:

(1) Sampler:—a bridge type relay is used. In this type of relay the output contact closing time is made variable according to the current

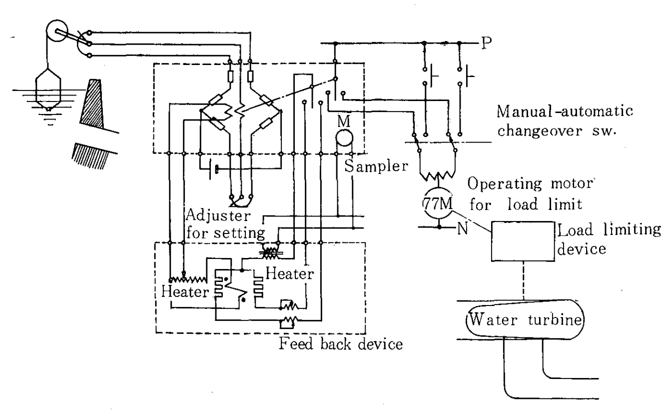


Fig. 4 Water level governor

flow through a Wheatstone Bridge galvanometer circuit. Three standard times are used for sampling: 9, 13.5, and 27 seconds. The sampler may be manufactured with a detection sensitivity in the order of several tens of μA's at a 100% input, and with an internal resistance of several tens of ohms.

(2) Feedback device:—when the above bridge relay is directly connected to the operating motor, only an integrated characteristic is indicated and therefore may not be used as a water level regulator. As was explained earlier, a water level governor operating in a stationary domain must possess integrating characteristics so as to eliminate stationary deviations. However, a simple integral is unstable and useless. Accordingly, in the areas where changes occur rapidly, not only differential characteristics must be added but a signal lag must also be compensated for; it is necessary, therefore, to have characteristics that include proportion plus integration. A feedbeck device with a thermo-couple added to the bridge relay (refer to *Fig. 4*) will fulfill the above requirement. *Fig. 5* shows the output voltage of the feedback device during one closing; cycle of the bridge relay contacts. If its negative feedback voltage is applied to the input of the bridge relay, a close approximation of the PD characteristic can be obtained from the control. *Fig. 6* shows a block diagram of this type of controller. If this controller is coupled to the operating motor, the position of the operating motor responds to the PD characteristic with I added so as to indicate a PI characteristic. The input of each section and the action related thereto are plotted in graphic form with the step input in *Fig. 7*. With this device, the previously mentioned time constant, T, may be obtained up to a maximum of 20 minutes.

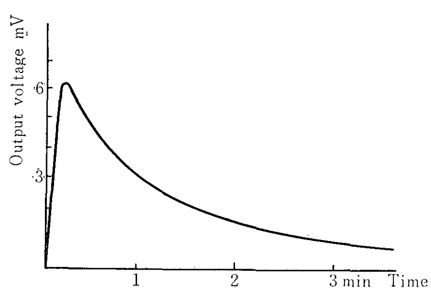


Fig. 5 **Indicial response of thermal return device**

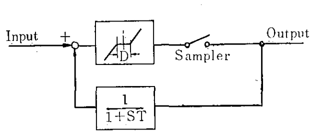


Fig. 6 **Block diagram of controller**

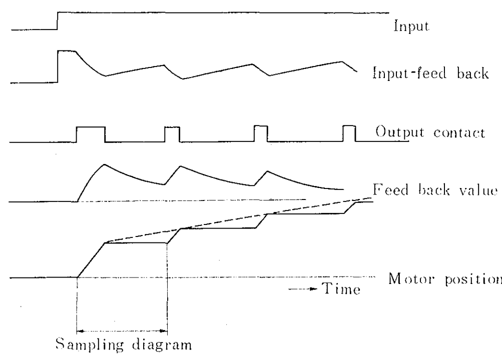


Fig. 7 **Operation diagram**

2) Continuous control system

The continuous control system utilizes a magnetic amplifier. This system is the same as the sampled data system in that it is given integrating characteristics. This type of system is used by power plants having comparatively small head reservoirs, where a rapid water level change will take place when the turbine guide vane is fully opened, or when a fast water flow into the reservoir is encountered. A block diagram of this system is shown in *Fig. 8*. In this

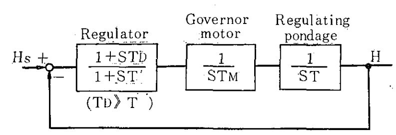


Fig. 8 **Block diagram of water level governor**

system the feedback device utilizes a time constant, T_D, of CR and its value is 0.1～1.0 minutes. This system is used most effectively by down river plants where a joint water level governor will automatically shut down the plant in the case of load interruption at the upstream station. To better explain: when an upriver station performs a 100% load trip, the down river plants, in a connected water course, will receive a full-close signal from the water level controller. The water tank level will continue to decrease up to the time of full closing. If this decrease, ΔH, and the time, tc, it takes for the turbine guide vane to fully close are plotted against the reservoir size, T, and the time constant, T_D, of the differential characteristic type controller, we obtain the curves shown in *Fig. 9*. Time, T_m, in this case is 30 sec. and is the time for operating motor, working at its rated voltage (100% voltage), to bring the turbine guide vane to a full open (open 100%) position from a full closed position. Pond size is determined as follows:

$$T = \frac{H(m) \cdot A(m^2)}{Q\,(m^3/\text{sec})}\ (\text{sec})$$

where H is the basic variation range (taken as 100%) as determined by the float variation range, etc.; A is the average pond area where the pond water level

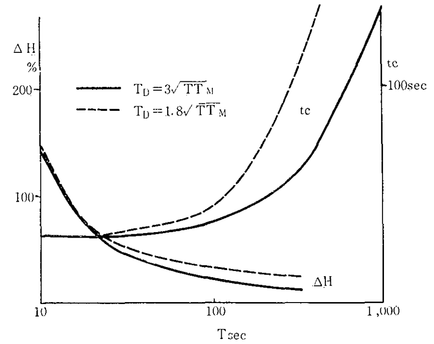


Fig. 9 ΔH versus T, tc versus T diagram

will vary within the range of H; Q is the water flow when the guide vane is in the full open position.

3) Output balancing device (joint operation)

When two or more generators jointly control the water level, it is necessary to have the output balanced between the generators. To accomplish this, a converter, one that will convert the output power to DC voltage, is necessary. A torque balancing type converter or a thermal converter is usually used.

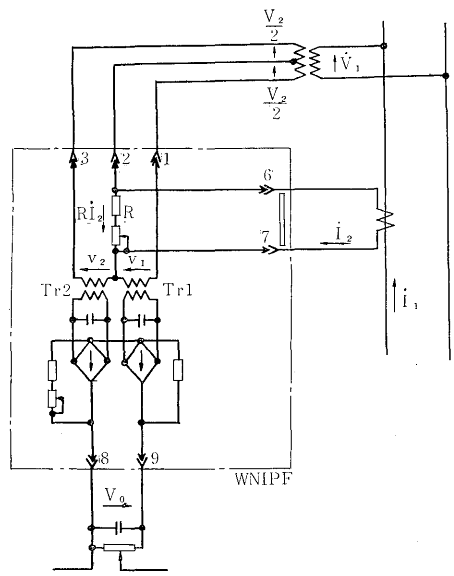


Fig. 10 Connection diagram of effective current detector

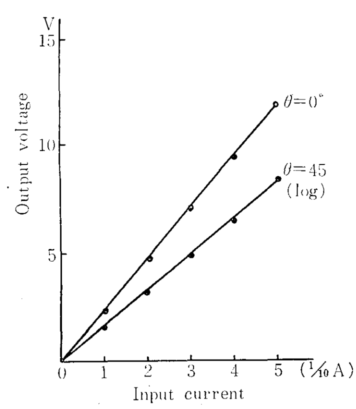


Fig. 11 Characteristics of WNIPF

Since the generators are connected in parallel on the main bus bar in the power station, it may be assumed that each generator is operating at nearly the same voltage; therefore, the adopted system utilizes the effective current, $I\cos\theta$, instead of the power to accomplish the balance. A device (WNIPF) that is used in changing the effective current into a DC voltage is shown in *Fig. 10*. The characteristic of the WNIPF are shown in *Fig. 11*. In the diagram, the voltage v_1 and v_2 that are impressed across T_{r1} and T_{r2} become $\frac{\dot{V}_2}{2}+R\dot{I}$, $\frac{\dot{V}_2}{2}-R\dot{I}_2$ respectively. Accordingly, if the secondary voltage Tr_1 and Tr_2 is rectified separately and the difference (absolute value of vector value) compared, the output voltage, V_0, when the phase angle between the line voltage and current is θ, and if a condition is chosen so that $\frac{\dot{V}_2}{2}/>>/R\dot{I}_2$, will be:

$$V_0=\left|\frac{\dot{V}_2}{2}+R\dot{I}_2\right|-\left|\frac{\dot{V}_2}{2}-R\dot{I}_2\right|\fallingdotseq 2\,RI_2\cos\theta$$

thus, a DC voltage proportional to the effective current may be obtained.

The input current linearity of this device is excellent with a tolerance of $\pm 1.0\%$. Input current phase angle error is 1.5%, with a power factor lag of 0.7, and near 0 power factor output voltage becomes at 87～88°. The output voltage variation caused by the input voltage variation is less than 1% over a range of 70～130 V. This effective current detector not only can be used as an output balancing device when combined with a water level controller, but also may be easily used in the joint operation circuit of a so-called electric governor.

2. Flow Regulating Device

A power plant that has been designated as a regulating power station requires an operation that will maintain a constant water out-flow. The outflow, Q, from a regulating pond, can be expressed as a function of the effective head, H, and guide vane opening, G, or:

$$Q=f_1(G, H)$$

To express G as a function of Q and H the following is used:

$$G=f_2(Q, H)$$

Where the relation of f_2, at effective head, H, will determine the opening of the guide vane to obtain the out-flow Q. Examples of this are shown in *Fig. 12* and *13*. Now, a function is generated by a function generator, that is, effective head H is detected from the float, shown in *Fig. 14*, if a DC voltage proportional to the head is generated, and a setting flow is given as a resistance variation, an output voltage proportional to the required guide vane opening is obtained. If this voltage is applied to the input of the bridge relay previously mentioned, and the voltage compared with the voltage from the guide vane ring tube, the vane will be set so as to permit

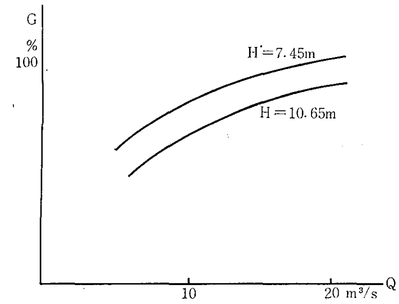


Fig. 12 **G versus Q diagram of water turbine**

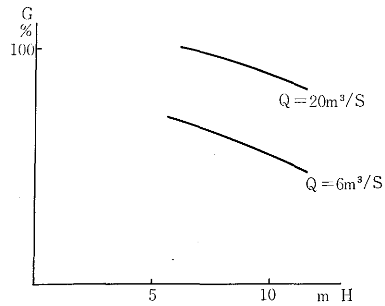


Fig. 13 **G versus H diagram of water turbine**

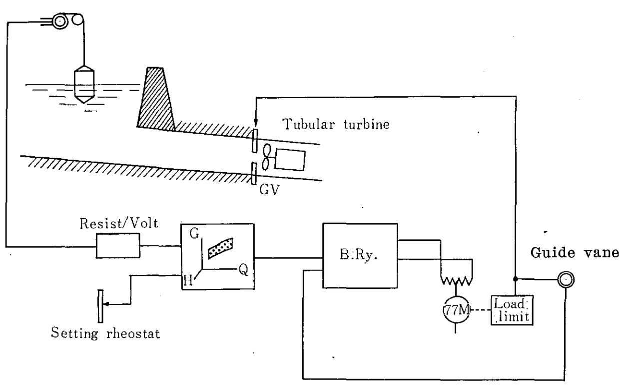


Fig. 14 **Block diagram of water flow governor**

the desired amount of flow. *Fig. 14* shows a function generator in which approximation by two tangentical straights is used for setting the flow and an approximation by one tangentical straight for the effective head. In this system functional forms are variable and can easily be adjusted at the time of site testing.

3. Electric Governor

Since our electric governor has been described in detail in *Fuji Electric Journal* before, we will touch only on the features of this device as seen from the application standpoint and on its auxiliary devices.

The generators in ordinary power plants are normally connected in parallel to the power system. Damping to stabilize the electric governor is not as necessary when the generators are run in parallel as it is when generators are not in parallel; i. e., at no load; in fact, it is desirable to decrease the amount of damping, from the standpoint of response, when in parallel operation. The electric governor manufactured by this company is designed so that it changes over contactlessly from no load damping to service damping when the guide vane opening becomes greater than a predetermined amount. *Fig. 15* shows the principle of this damping circuit. V_G is a voltage proportional to the guide vane opening and V_{G0} is an equivalent voltage at the time of damping change-over and has the same proportional constant (this value adjusts R_G and is variable over the opening range of 5∼35%) which acts as bias. Therefore, the voltage at the A end of the two gang potentiometer, R_P, is positive when the guide vane opening is smaller than predetermined opening whereas the voltage at the B end will become positive when the guide vane opening is larger than the predetermined amount. While the A end is positive, damping output is determined by the vane of the circuit of A-R_{28}-R_1-C_1-R_{e2}-B, and during the time that the B end is positive, it is set by the circuit of B-R_{e1}-R_k-R_{26}-R_{e3}-C_1-R_1-R_{28}-A (damping when loaded may be adjusted by R_k). Thus, with V_{G0} as the boundry, the amount of damping can be varied. Power plants do not always operated in parallel with other power systems. Sometimes they take the load singly, and at times while operating in parallel with other power systems, because of the opening of a far away tie line circuit breaker, they may take the local load as a single system.

In cases such as this, guide vane opening is in the range of service damping, whereupon the damping amount is insufficient and the device becomes unstable. This must be detected by some means and the damping amount increased until the single system becomes stabilized. Our company has a hunting

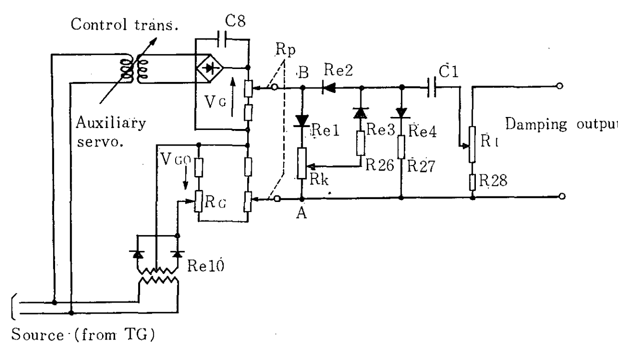


Fig. 15 **Damping circuit diagram**

relay which detects this insufficiency and short-circuits both terminals or R_{e2} by means of a contact and thereby increases the damping amount until it is approximately equal to that at the time of no load. Next, we will discuss the hunting relay.

When hunting occurs, the guide vane is naturally opening and closing according to a certain cycle. If a DC voltage proportional to the guide vane opening is differentiated with respect to *CR,* a differential current as shown in *Fig. 16* will flow. This current is proportional to *dG/dt.* In normal operation, there will be a variation in the vane opening, however,

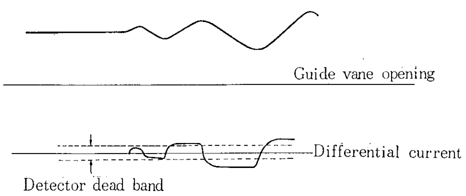


Fig. 16 **Operation diagram of hunting relay**

the change is small and the cycle is long. Accordingly, if the differential current exceeds a dead band, Δ, and if it further detects that its direction has changed during a certain time, *T*, it is possible to differentiate between hunting and the following of a system load variation. The setting of the hunting relay is accomplished by establishing a dead band range, Δ, and a direction reversing time, *T*.

4. Field Exciting Device, AVR

On the other hand, if we turn our attention to the field exciting device, AVR, we will find that about 70% of the generators recently delivered to users have a static compound type field exciting device and almost all of the large capacity machines are equipped with an OH type. We would like to point out that 80% of the field exciting devices with rotary exciters have compound type characteristics, with an added current component, with a view toward quick response. We will pick out the important features of the input of the control section that is an accessory to all field exciting devices and explain them. *Fig. 17* shows a block diagram of the detector for Fuji Denki's AVR (SG-AVR, Model 60), AVR is composed of the following various mixed inputs:

(1) Positive phase sequence voltage detector
(2) Non-linear voltage droop characteristic factor
(3) kVA limiting factor
(4) Current limiting factor

In the detector circuit $I \sin(\theta-\theta_0)$, θ_0 is the set power factor angle and θ is the current phase lagging angle, and when used for APFR, a DC voltage approximately proportional to $I \sin(\theta-\theta_0)$ can be obtained. This is added as a control signal to the

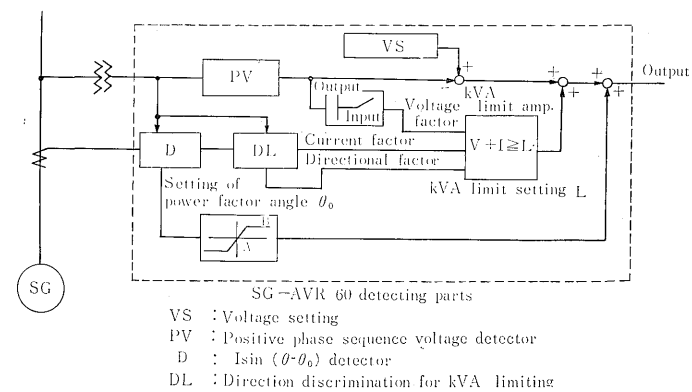


Fig. 17 **Block diagram of input parts of AVR**

ΔV signal through a non-linear circuit. When $I \sin(\theta-\theta_0)$ is large, when the deviation from the set power factor is large, the droop characteristic becomes small and the AVR displays its proper characteristics. *Fig. 18* shows the characteristics of APFR. It is clear that if the "*A*" characteristic shown in *Fig. 18* is removed, the device will operate

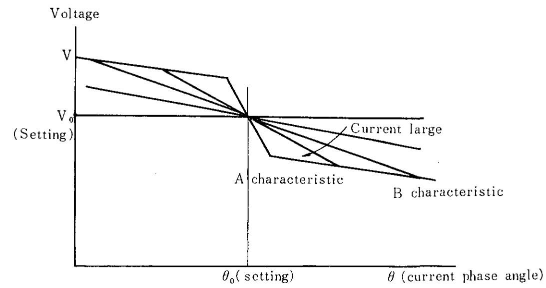


Fig. 18 **Characteristics of APFR**

as an ordinary AVR. The important feature of this APFR is that when a system becomes a single system, it can change over automatically to stable AVR operation in the range of *B* characteristics without a large voltage variation caused by the difference between the load and power factor setting.

In the kVA limiting amplifier circuit, the kVA limiting should be performed by the value *VI*, but actually it is done by an amount that exceeds the value of $V+I$, thereby issuing a stronger instruction signal than the other detectors. It will issue a voltage lowering instruction when the $V+I$ value is higher at the lagging phase side and a voltage raising instruction when the $V+I$ value is higher at the leading phase side.

A generator is thermally limited by kVA, so that when there is an appreciable voltage drop the current is not permitted unconditionally to increase to maintain a constant kVA. This AVR detector will give the characteristic shown in the diagram as a voltage input factor of the kVA limiting part, and as the voltage drops, it will keep the voltage seemingly steady under a certain value of input voltage and from the $V+I=$constant relationship it will prevent the current from increasing any farther, which indicates a current limiting characteristic.

5. Stopping Detecting Relay

Accurate confirmation as to the starting and stopping of the turbine, especially with pump turbines which reverse the direction of rotation, is very important. This relay utilizes the principle that the current flowing in an inductance is approximately constant based on the fact that a permanent type tachometer-generator's voltage is proportional to frequency.

Namely $I=\frac{V}{Z}=\frac{k_1 n}{k_2 n}=\frac{k_1}{k_2}=$constant.

With this device, a detection of approximately 1～2 rpm is possible.

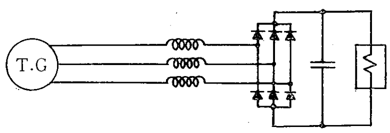
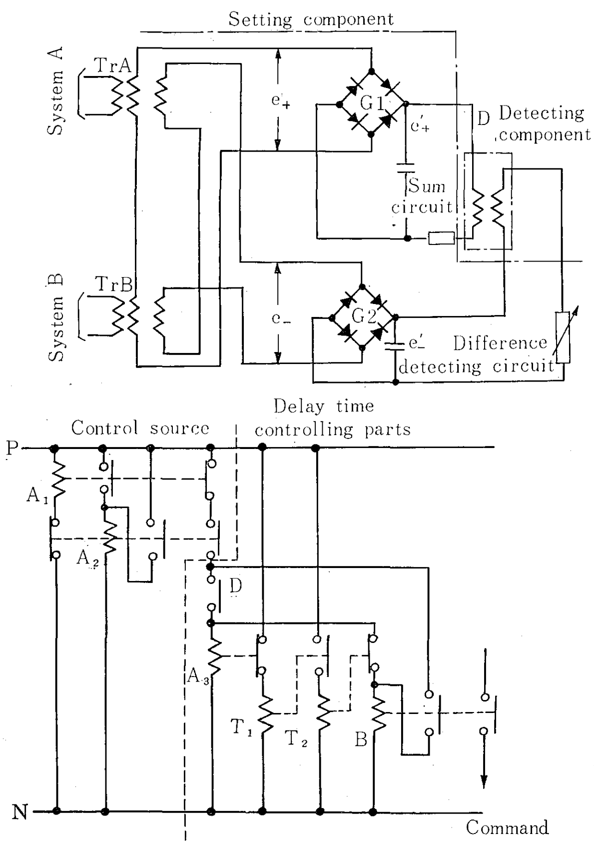


Fig. 19 Connection diagram of low speed relay

6. Slip-detecting Relay

This relay is used to detect slip when the synchronizing method is used in which the synchronous motor of an auto-sychronizing generator or a pump turbine is started as an induction motor with the field being excited after reaching the pull-in slip necessary for synchronization. This relay will detect a slip ranging from 0.1～3%, *Fig. 20* shows its internal connections. The tachometer dynamo output and line voltage are supplied to the termimals of the *A* and *B* systems, whereby the voltage sum and voltage difference of both systems are obtained, rectified, and supplied to the differential detecting relay. As shown in *Fig. 21,* when time T_D, between the intersections of the sum voltage and voltage difference, exceeds a predetermined time, slip is detected.



$A_1A_2A_3B$: Auxiliary relay
T_1T_2 : Slow release type aux. relay

Fig. 20 Connection diagram of slip-detecting relay

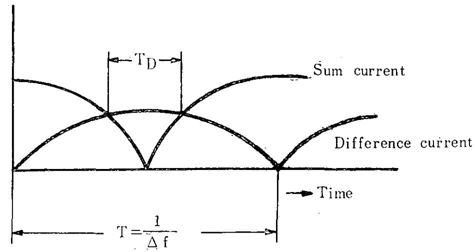


Fig. 21 Operation diagram of slip-detecting relay

IV. CONCLUSION

We have introduced and explained a few of Fuji Denki's control devices and methods which have been discussed often and which are in actual use at many power plants. We are sorry that due to a lack of space our discussion had to be limited to only important points. Today, the operation of power plants shows a tendency toward a concentrated control employing more accurate and varied control devices. The weak current electrical techniques, which had been regarded as a separate field before, has been completely fused with that of the heavy current to be adopted in the power equipment. Development in the field of semi-conductors has added further impetus. Semi-conductor products are now extensively found in today's power plants,

The writers will be pleased if this article can be of any help to those who are already working in the field of power plant maintenance, or those who are planning construction of new power plants.