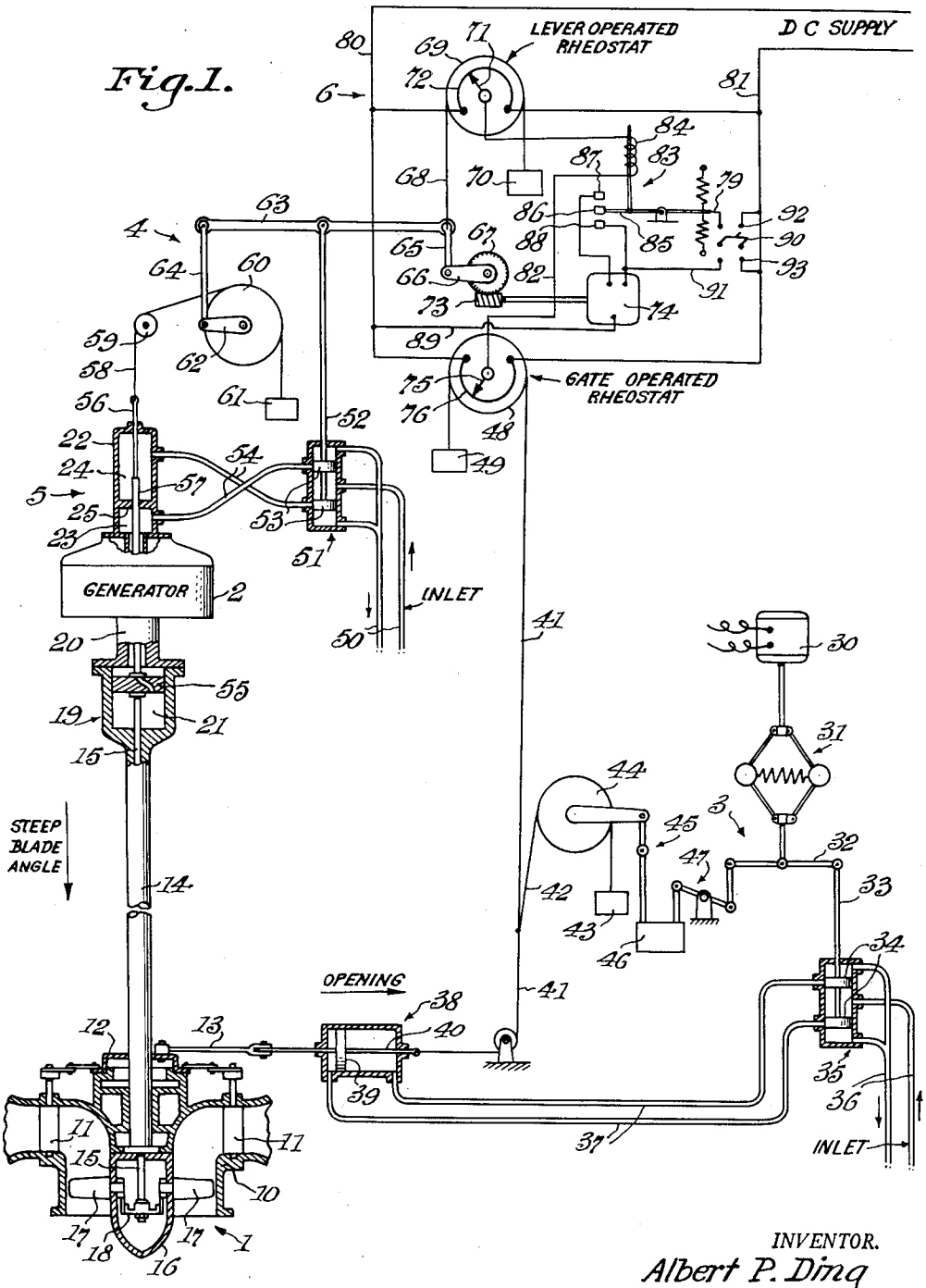
May 30, 1961 A. P. DING 2,986,646

CONTROL FOR CHANGING BLADE ANGLE OF ADJUSTABLE BLADE TURBINE

Filed March 18, 1954 4 Sheets-Sheet 1

Fig. 1.



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CONTROL FOR CHANGING BLADE ANGLE OF ADJUSTABLE BLADE TURBINE

Filed March 18, 1954 4 Sheets-Sheet 2

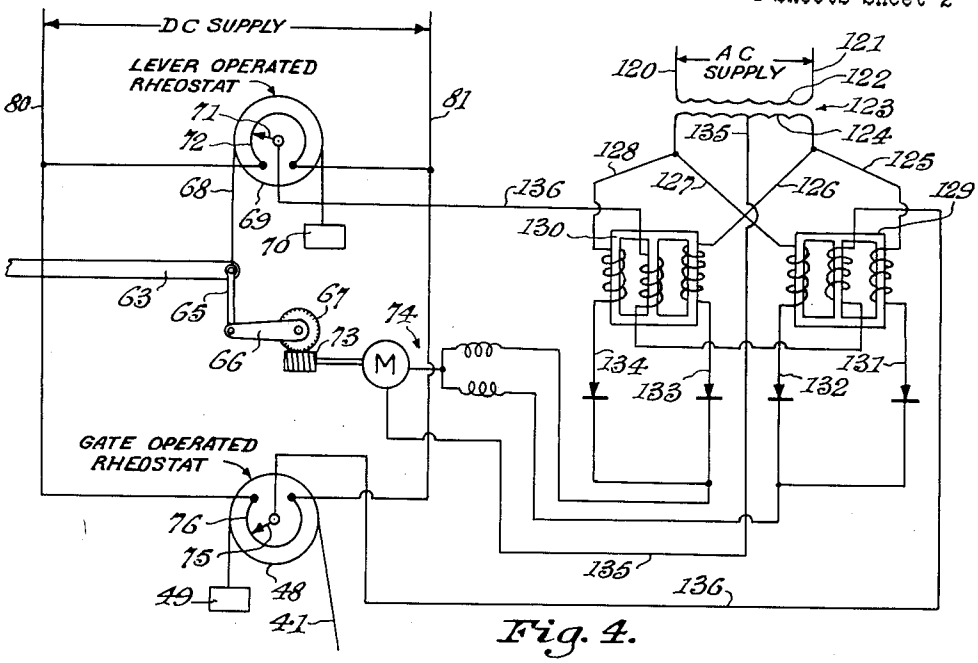


Fig. 4.

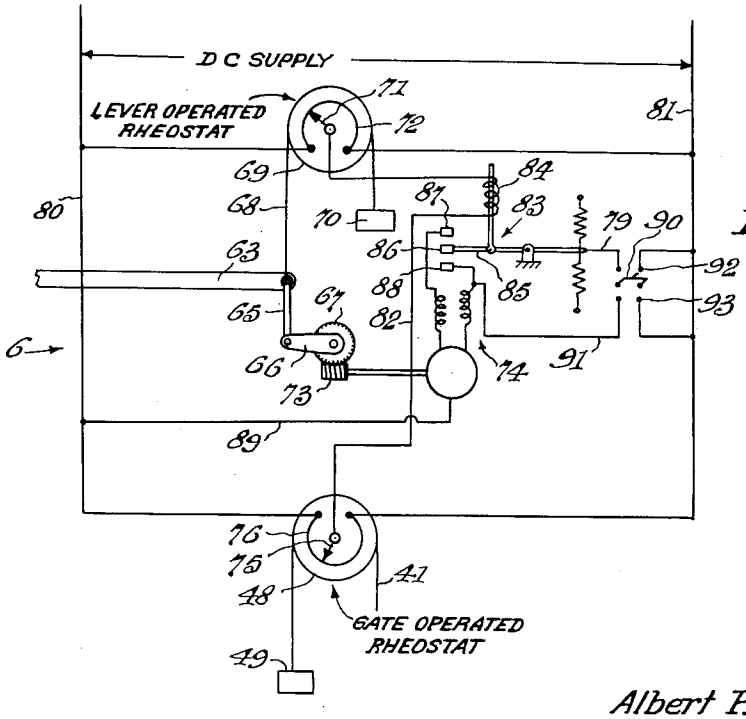


Fig. 2.

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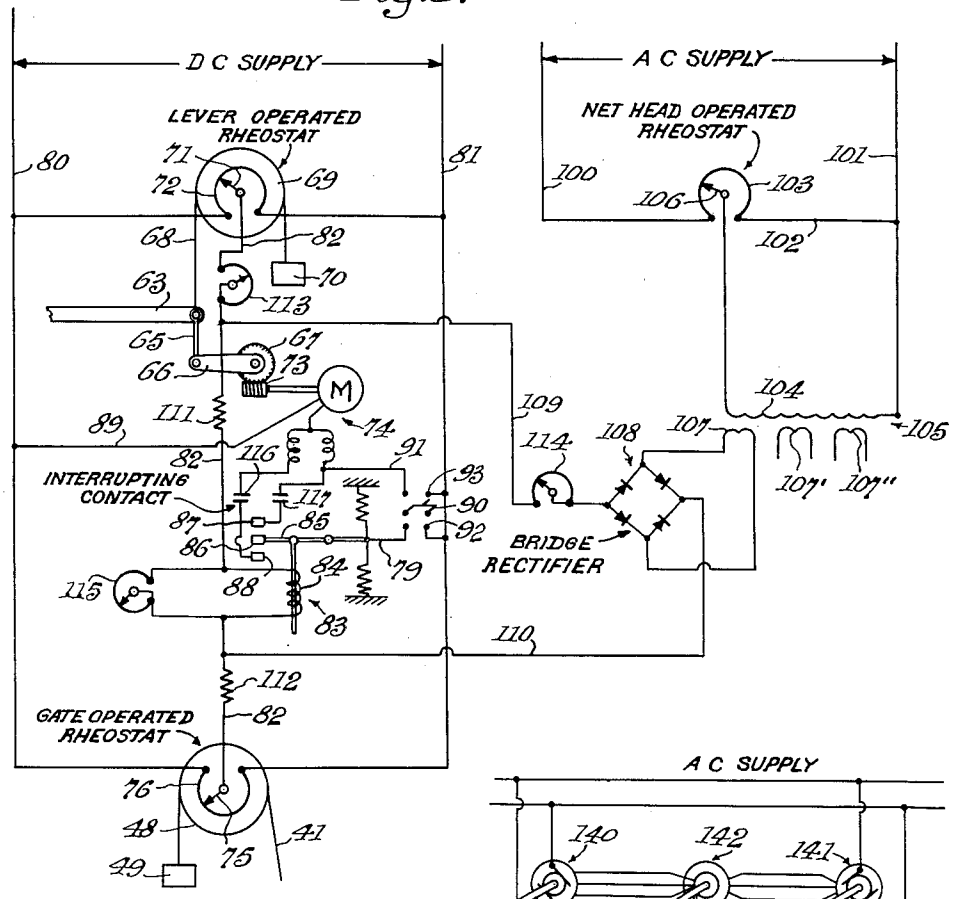
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May 30, 1961 A. P. DING 2,986,646

CONTROL FOR CHANGING BLADE ANGLE OF ADJUSTABLE BLADE TURBINE

Filed March 18, 1954 4 Sheets-Sheet 3

Fig.3.



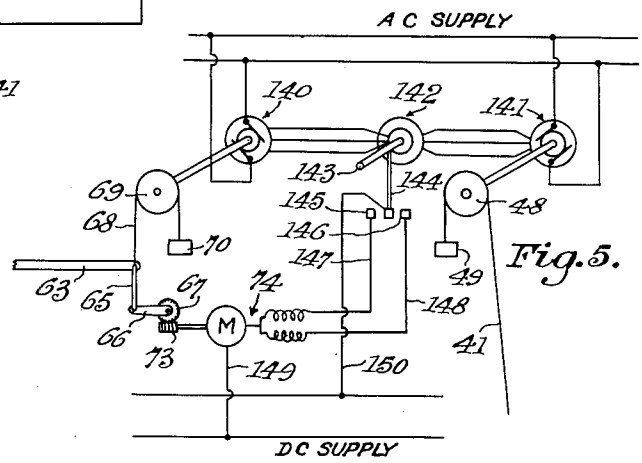
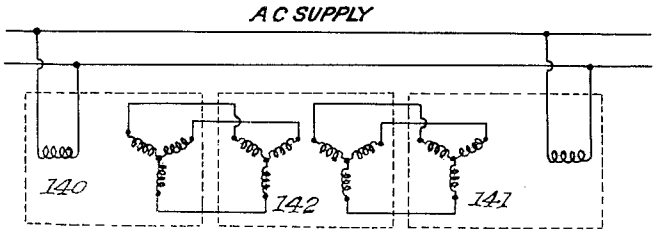


Fig.5.

Fig.6.



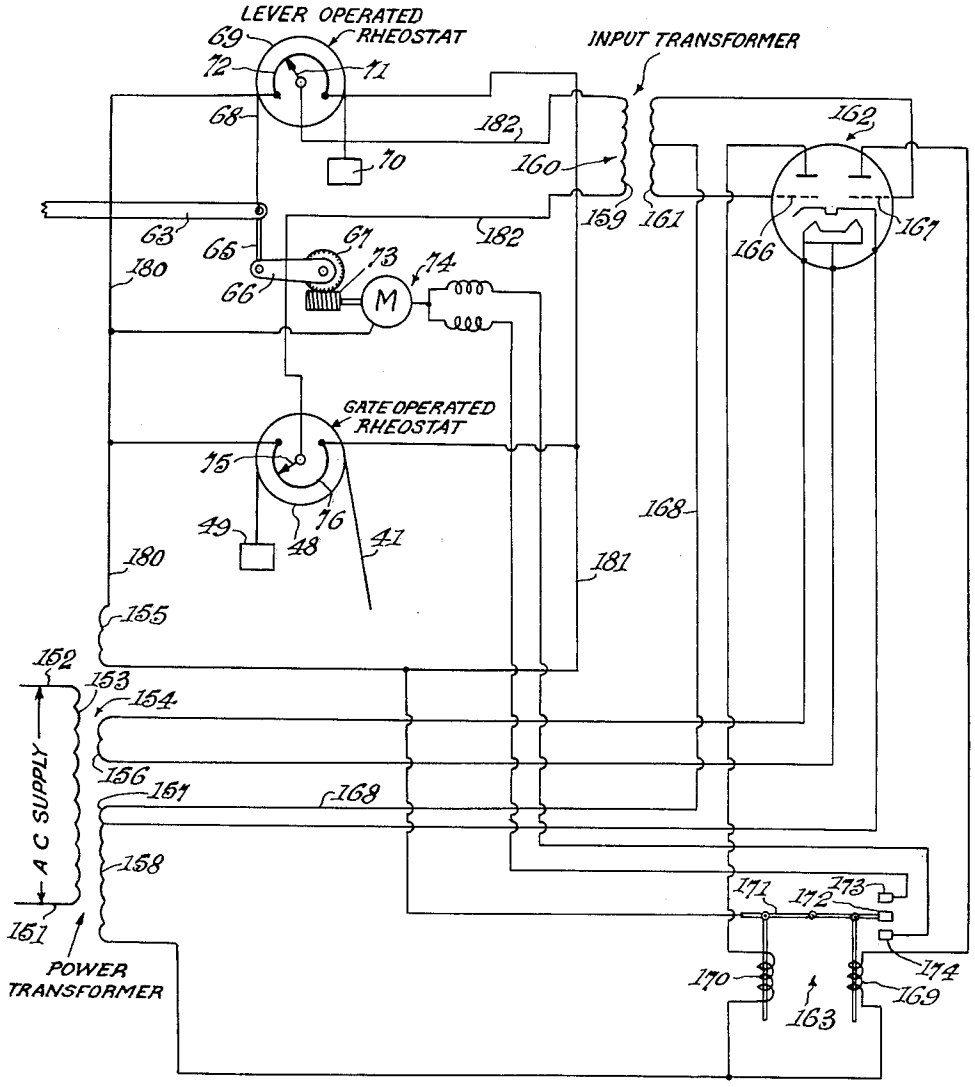
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CONTROL FOR CHANGING BLADE ANGLE OF ADJUSTABLE BLADE TURBINE

Filed March 18, 1954 4 Sheets-Sheet 4

Fig. 7



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United States Patent Office 2,986,646 Patented May 30, 1961

2,986,646

CONTROL FOR CHANGING BLADE ANGLE OF ADJUSTABLE BLADE TURBINE

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Filed Mar. 18, 1954, Ser. No. 417,239

15 Claims. (Cl. 290—40)

(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the Government for governmental purposes, without payment to me of any royalty thereon.

The present invention relates to an improved method of changing blade angle of an adjustable blade hydraulic turbine responsive to changes in wicket gate opening and net head and is particularly useful in a system in which wicket gate opening is changed responsively to the speed of the generator propelled by the turbine.

The blade angle of adjustable blade turbines customarily used are adjusted by means of a mechanical linkage and cam construction directly responsive to motion of a servo-motor or other mechanical device for opening or closing the wicket gate including cams operating on floating levers which when moved from their original position, operate a hydraulic servo-motor changing the blade angle. In systems of this type it is normal practice to make further changes in the blade angle of the adjustable blade turbine by means of cams operated manually by an attendant to the turbine. A series of cams are available for selective use depending upon the range of net head and indicated by measuring devices of the head in the fore and tail races of the turbine. An arrangement of this type necessitates a constant observation on the part of the attendant and results in periodic inefficient setting of blade angle resulting from a change of net head that is unobserved by the attendant and does not provide for minute adjustment for the most efficient operation in the face of all variations of net head within range of a particular cam.

An important object of this invention is to provide a control system for adjustable blade turbines to constantly maintain predetermined relations between blade angle and combined gate opening and net head conditions.

Another object of this invention is to provide a governing system for hydraulic turbines which will maintain predetermined relations between the blade angle and combined gate opening and net head conditions and accurately follow the true relationship for maximum efficiency.

Another object of this invention is to provide a governing system for hydraulic turbines wherein predetermined relations between blade angle and combined gate opening and net head conditions are maintained automatically by means of a basic electrical-mechanical governing system which acts responsively to the speed of the generator, the wicket gate opening and the net head.

Another object of this invention is to provide an electrical control system for changing the blade angle of an adjustable blade turbine responsive to the wicket gate opening of the same turbine.

Another object of this invention is to provide an electronic control circuit for changing the blade angle of an adjustable blade turbine responsive to the wicket gate opening of the same turbine.

Another object of this invention is to provide an electrical circuit controlled by an electrical device for the measurement of net head which will influence the electrical circuit contained in an electrical hydraulic-mechanical system for changing the blade angle of an adjustable blade turbine in order that the blade angle will reflect conditions of net head.

Another object of this invention is to provide an electrical control circuit responsive to variations in two variables to effect variations in one variable responsive to variations in the other variable.

Other objects and advantages of the invention will be apparent as the description proceeds and the features of novelty will be pointed out with particularity in the appended claims.

Briefly, in accordance with this invention there is provided a hydraulic turbine having adjustable blade and adjustable wicket gate openings, a generator driven by the turbine and hydraulic servo-motors operating mechanical linkage to change the adjustable blades of the turbine and the wicket gate. The hydraulic servo-motor controlling the wicket gate opening is controlled by a governor arrangement attached to an electric motor propelled by electricity generated by the generator, so that a drop in power generated will cause an increased opening of a wicket gate and an increase of current generated will cause a decrease of wicket gate opening. There is also provided an electrical-mechanical system responsive to the opening of the wicket gates for operating the hydraulic servo-motor which controls the blade angle.

In operation, as the electric motor of the governing system either speeds up or slows down, the hydraulic servo-motor is caused to operate, changing the wicket gate opening and at the same time influencing the governing system to cause the hydraulic servo-motor to cease functioning. Responsive to changes of position of the piston of the hydraulic servo-motor just mentioned, a mechanical system changes the setting of a variable rheostat in an electric circuit which basically comprises two adjustable rheostats in a direct current circuit and having a by-pass interconnecting the contact arm of the two rheostats constituting a form of a Wheatstone bridge. The change in rheostat setting caused by the servo-motor controlling the wicket gate opening just described will cause an unbalance in the Wheatstone bridge and a flow of current across the by-pass between the contact arms of the two rheostats.

Included in the by-pass in the preferred embodiment of the invention to form a balancing circuit, is a relay coil having a movable plunger to operate a single pole, double-throw switch in a motor circuit to selectively activate one or the other of the two windings of a reversible electric motor. Operation of this electric motor will cause operation of the hydraulic servo-motor controlling blade angle through a mechanical arrangement including a float bar and a valve attached thereto in the hydraulic system supplying power to the servo-motor. Operation of the servo-motor will, in addition to changing blade angle, cause a reaction in the mechanical system including the floating bar controlling the valve in the hydraulic system to adjust the second rheostat described above.

Sufficient change in setting of the second rheostat will bring about a situation in which both rheostats have comparable settings, in which the circuit is in balance and no current will flow through the by-pass connecting the contact arms of two rheostats and consequently the plunger of the relay will return to normal, and the motor will remain inactive. At this point of balance, the blade angle has the proper setting for the wicket gate opening then existing. Further blade-angle adjustment may be caused by further activation of the same relay by an electric current flowing through a circuit including the relay described above, and in the preferred embodiment, a bridge rectifier and a secondary winding on a coil in an alternating primary circuit including a rheostat which is controlled by and actuable responsively to electrical measuring devices for registering the net head.

There are also provided alternate balancing circuits.

One of these includes a saturable reactor and dry disc rectifier combination which when powered by a separate A.C. source will interpret directional current in the by-pass of the Wheatstone bridge to activate one winding of the reversible electronic motor driving the float bar controlling the blade adjustment to rebalance the system.

Another alternative balancing system contemplates use of a selsyn system for adjustment of the blade angle by substituting the primary rotors of the selsyn system for the variable rheostats of the bridge, and using the rotor of an intermediate differential positioning device to activate alternatively contacts controlling the two fields of a reversible D.C. motor driving the blade angle adjustment float bar to effect blade adjustment and rebalance the system.

Another alternative arrangement includes a primary winding of a transformer in the by-pass circuit of the bridge and additional circuits powered by a separate A.C. power transformer to a dual triode electronic tube wherein the grid circuit includes the secondary winding of the transformer in the by-pass circuit so that the grid circuit may act to cause one plate of the tube to be active while the other is blocked responsive to direction of the current in the by-pass, to cause operation of a relay in the plate circuit to activate the appropriate winding of the motor driving the float bar to effect blade adjustment and rebalance the bridge.

In the accompanying drawings, forming a part of this specification, and wherein like numerals are employed to designate like parts throughout the same:

Fig. 1 is a diagrammatic view of a complete system of the device including the preferred embodiment of the balancing system to adjust blade angle responsive to wicket gate opening and showing various elements partly in elevation and partly in vertical section;

Fig. 2 is a schematic diagram of the preferred embodiment of the electrical arrangement for adjusting blade angle responsive to changes in gate opening;

Fig. 3 is a schematic diagram of the preferred embodiment of the balancing circuit modified by the inclusion of a bridge rectifier circuit for adjusting blade angle responsive to changes in both gate opening and net head;

Fig. 4 is a schematic diagram of a modification of the balancing circuit including a saturable reactor and dry disc rectifier combination for adjustment of blade angle responsive to changes in gate opening;

Fig. 5 is a diagrammatic view of a modification of the invention including a selsyn device showing the mechanical linkage between the rotors of the selsyn system and the mechanical portions of the system as shown in Fig. 1;

Fig. 6 is a schematic diagram of the electrical circuits of the selsyn system of Fig. 5;

Fig. 7 is a schematic diagram of a modification of the invention using an electronic tube for activation of the motor which initiates blade angle adjustment responsive to changes of gate opening.

In Fig. 1 of the drawings, wherein for the purposes of illustration there are shown preferred embodiments of the invention, the basic form of the invention is illustrated diagrammatically as applied to an adjustable blade, adjustable gate hydraulic turbine **1** driving a conventional electric current generator **2**. The blades and gates of the turbine are adjusted by electrical-hydraulic-mechanical systems including a hydraulic-mechanical system indicated generally by **3** for adjustment of the wicket gates of the turbine responsive to the speed and frequency of the generator **2** and an electrical-hydraulic-mechanical system **4** for adjustment of the blade angle responsive to gate opening or adjustment. This latter system includes a hydraulic-mechanical subsystem **5** to effect changes in blade angle and a mechanical-electrical subsystem **6** to control the hydraulic-mechanical subsystem **5**.

Turbine **1**, of the adjustable blade type, has the usual casing **10** forming a peripheral water inlet in which are mounted a plurality of movable wicket gates **11** journaled in the casing and being interconnected by conventional linkage to an operating or shifting ring **12** to which is attached gate operating or shifting rod **13** to effect opening or closing of the wicket gates responsive to movement of the rod **13**. The turbine **1** is connected with the generator **2** by a hollow drive shaft **14** through which extends blade operating rod **15** and which, at its end, is provided with a hub **16** within the casing **10**.

Journaled in hub **16** are a plurality of radially extending adjustable blades **17** which are connected within the hub by conventional linkage, including a cross head **18**, to blade operating rod **15**. Hollow drive shaft **14** is provided with an enlarged portion **19** at its end opposite from the hub **16** to form a cylinder **21**, the purpose of which will hereinafter be described in detail. Generator **2** is provided on one side with a hollow generator shaft **20**, one end of which is connected to the enlarged end **19** of the drive shaft **14** for mutual revolution therewith and forms a cylinder head for blade operating cylinder **21**. The other side of generator **2** is provided with housing **22** which is divided into chambers **23** and **24** by partition **25**.

The hydraulic-mechanical system **3** for adjustment of the wicket gates **11** responsive to the speed and frequency of generator **2**, is similar to those now in use and includes a motor **30** powered by current produced by generator **2** driving a flyball governor **31** to which is pivotally connected a floating lever **32**. Pilot valve rod **33** is connected to one end of floating lever **32** and carries pistons **34** located within pilot valve **35**. Pipes **36** and **37** connect pilot valve **35** with a source of fluid under pressure, and hydraulic servo-motor **38** respectively. Servo-motor **38** contains piston **39** mounted on a straight-through piston rod **40**, which is secured at one end to gate operating rod **13** and at the other to cable **41**.

Attached to cable **41** for corresponding movement therewith is a second cable **42** which, with counterweight **43**, pulley **44**, linkage **45**, compensating mechanism or dashpot **46**, and linkage **47** attached to floating lever **32**, constitutes a rebalancing means for the hydraulic-mechanical wicket gate adjusting system **3**. With the systems in balance as illustrated in Fig. 1, if the speed of motor **30** decreases due to a decrease in speed of generator **2**, the resulting deceleration of flyballs **31** cause floating lever **32** to drop slightly pivoting about the connection with linkage **47**, forcing pistons **34** down permitting fluid under pressure to be conveyed by pipes **37** to the left side of piston **39** in servo-motor **38**, forcing the piston and shifting rod **13** to the right opening wicket gates **11**.

Movement of gate operating rod **13** is accompanied by a corresponding movement of cables **41** and **42**, counterweight **43**, pulley **44**, linkage **45**, compensating mechanism **46**, linkage **47**, and floating lever **32**. Floating lever **32** pivots about its connection with the flyball system moving pistons **34** upward to their original positions stopping flow of fluid through pipes **36** and **37**.

The blade angle of the turbine is automatically adjusted responsively to the gate opening to maintain the most efficient setting of blade pitch for each wicket gate setting by the electrical-hydraulic-mechanical system indicated generally at **4** and composed of the hydraulic-mechanical blade angle set subsystem **5** and the mechanical-electrical blade angle control subsystem **6**.

Blade angle set subsystem **5** is powered by hydraulic pressure furnished from a source through pipes **50** to pilot valve **51** provided with pilot valve rod **52** carrying pistons **53** to control the flow of the hydraulic fluid to pipes **54**, which conduct the fluid under pressure through the housing **22** and tube **57** of generator **2** to the hydraulic blade servo-motor or blade operating cylinder **21** containing piston **55**, which is attached to blade operating rod **15** and to blade operating tube **57**. Blade operating rod extension **56** extends from tube **57** to which it is attached and out through the top of housing **22**.

Blade-operated cable 58 is attached to the exterior end of blade operating rod extension 56 and extends over idler pulley 59 and floating lever pulley 60, and terminates in counterweight 61.

Floating lever pulley 60 is provided with a crank arm 62 having a common center of rotation with the pulley. Blade operated floating lever 63 is operatively connected at one end to crank arm 62 by means of link 64, is pivotally connected to valve rod 52 at its mid-point and is pivotally connected at its other end to link 65 which is also pivotally connected to crank arm 66 of gear 67. Blade balance cable 68 is also connected at one end to the joint between floating lever 63 and link 65 and extends over blade balance pulley 69 terminating in counterweight 70 to operate control arm 71 of blade balance rheostat 72 that is mounted on the same shaft as is pulley 69. Gear 67 is meshed with worm gear 73 which is driven by reversible motor 74.

The mechanical-electrical blade angle control subsystem 6 directs blade angle set subsystem 5 responsively to variations of wicket gate adjustment through actuation of pilot valve 51 responsively to movements of main cable 41 which runs over gate pulley 48 and terminates in counter-weight 49. Contact arm 75, of the gate operated rheostat 76 is mounted on a common shaft with gate pulley 48 for common rotational movement so that movement of main cable 41 in either direction is accompanied by corresponding movements of pulley 48 and contact arm 75 relative to gate operated rheostat 76, which is fixed against rotational movement resulting in a changed influence of the electrical circuit into which rheostat 76 is incorporated and which will presently be described.

The blade angle control subsystem 6 also includes a basic electrical blade adjustment circuit, as best illustrated in Fig. 2, including lines 80 and 81 from a D.C. supply, which may be used to operate a plurality of similar units, rheostats 72 and 76 connected across lines 80 and 81 in parallel, and wire 82 connecting relay 83 between contact arms 71 and 75 of the rheostats to constitute a Wheatstone bridge circuit. Rheostats 72 and 76 may be either evenly or tapered wound to produce a linear or non-linear relationship. Relay 83 includes coil 84 and spring biased armature 85, terminating at one end in contact 86, which is free to oscillate between contacts 87 and 88 and which is also electrically connected to line 81 at the other end. Contacts 87 and 88 are each attached to one field of reversible motor 74 which is grounded to line 80 by wire 89.

As previously described, a change of speed of generator 2 due to change of load or hydraulic conditions is accompanied by a change of speed of motor 30, powered by current generated by generator 2, causing a movement of floating lever 32 and an opening of valve 35 to permit fluid under pressure to flow through pipes 37 and operate servo-motor 38.

Servo-motor 38 adjusts the setting of wicket gates 11 and causes a movement of main cable 41 which, through cable 42 and the compensating mechanism of the gate adjustment means 3, previously described, stops operation of servo-motor 38. Movement of main cable 41 also rotates gate pulley 48 and contact arm 75 of rheostat 76, unbalancing the blade adjustment circuit of gate adjustment subsystem 6 with a resulting flow of current between contact arms 71 and 75 through wire 82 and coil 84 operating relay 83, to cause contact 86 to close against either contact 87 or contact 88, which permits current to flow through armature 85, motor 74, and wire 89, thereby causing motor 74 to operate in one direction or the other, depending upon the field activated by contact 87 or 88.

Operation of the motor 74 drives worm 73 and gear 67, causing crank arm 66 and link 65 to move floating lever 63, valve rod 52 and pistons 53, thus opening valve 51 to permit fluid under pressure to flow through pipes 54 and chambers 23 and 24 of housing 22. Flow of this fluid into blade servo-motor or operating cylinder 21 is accompanied by a movement of blade operating piston 55, and blade operating rod 15 in a direction dependent upon the direction of the opening of valve 51.

Blade operating rod 15 moves cross head 18 to rotate blades 17 uniformly about their axes, increasing or decreasing the blade angle of turbine 1. Movement of piston 55 and blade operating rod 15 is also accompanied by a movement of blade operating rod extension 56, tube 57 and blade operated cable 58. Cable 58 rolling across floating lever pulley 60 causes crank arm 62 and link 64 to move floating lever 63 in a direction that will cause pistons 53 to be restored to a central or closed position to stop further change of blade angle. The initial movement of floating lever 63, as caused by motor 74 is also accompanied by a movement of balance cable 68 and a rotation of balance pulley 69 which moves contact arm 71 of rheostat 72 in a direction corresponding to the movement of contact arm 75 of rheostat 76 caused by movement of main cable 41.

When contact arm 71 of rheostat 72 reaches the point which is the electrical equivalent of the position of contact arm 75 of rheostat 76, current will cease to flow through relay 83, causing armature 85 and contact 86 of the relay to be centered, breaking contact and stopping motor 74. At this point, turbine 1 has assumed the proper blade angle to correspond to the increased or decreased opening of wicket gates 11.

This system permits adjustment of blade angle responsive to the single variable influence of wicket gate opening but does not allow for differential adjustments of blade angle to reflect varying conditions of net head which must be considered in order to establish the most efficacious relationship of blade angle to gate opening.

Because the correct blade angle setting for a particular wicket gate opening at normal operating speeds does not provide sufficient torque for starting a turbine, there is also provided as best illustrated in Fig. 2, a starting arrangement in the form of an alternate circuit bypassing the relay and including double pole double throw switch 90 and wires 79 and 91 connected to terminals 92 and 93 of the switch for manual operation of the appropriate field of motor 74 to increase blade angle to the maximum. Switch 90 in effect overrides the influence of wicket gate setting on the blade angle and permits a set of maximum blade angle until the turbine gains sufficient speed to permit the automatic control system to operate efficiently.

In Fig. 3 there is illustrated a blade adjustment circuit which while controlling blade angle responsive to changes in wicket gate opening, as does the basic circuit shown in Fig. 2, has refinements to reflect conditions of net head in the setting of the turbine blade angle. The refined circuit includes rheostats 72 and 76, relay 83, and motor 74 for the same purposes that those elements performed in the basic circuit shown in Fig. 2 and also includes a biasing circuit which influences the operation of the basic circuit responsively to variations of net head. The biasing circuit includes lines 100 and 101 connected to an A.C. current supply across which is connected wire 102 into which is introduced rheostat 103. Primary winding 104 of transformer 105 is connected to line 101 and to contact arm 106 of rheostat 103. Net head operated rheostat 103, as operated by a commercial type controller utilizing resistance measurements from rheostats controlled by water levels in the fore and tail races of the system, provides a measurement of the net head in an electrical resistance which is proportional to the net head.

The secondary windings 107, 107', 107'' are provided to permit rheostat 103 to influence a plurality of control circuits so that one device for the measurement of net head may control a bank of hydro-electric generators. Current induced in coil 107 is fed to bridge rectifier 108

to produce a substantially direct current proportional to the net head suitable for introduction into the main portion of the blade adjustment circuit. Bridge rectifier **108** is also connected by wires **109** and **110** to wire **82** so that the rectified current passes through relay **83**. By this means the turbine blade angle is biased in a predetermined direction in an amount proportional to the net head. The current of secondary winding **107** may be converted by any full wave rectifier and is not dependent on use of a copper oxide rectifier as illustrated.

This biasing circuit operates to introduce the second independent variable of net head into the blade angle control system so that the blade angle is a combined function of wicket-gate opening and net head. The net head is measured as an electrical resistance and introduced into an A.C. master circuit where it is available as a control to a plurality of turbine blade angle control systems. This proportional alternating current is then utilized as a source of an induced secondary alternating current proportional to the net head and which when rectified by a dry disc bridge rectifier or other full-wave rectifier into a substantially direct current proportional to the net head and added to the basic control circuit will bias the blade angle of the turbine by adding to or detracting from the flow of direct current across the bypass between rheostats **72** and **76** through relay **83** as caused by an unbalance in the settings of rheostats **72** and **76**. The result of this biasing current is that contact arm **71** of rheostat **72** will assume a position other than that which is the electrical equivalent to control arm **75** of rheostat **76** when relay **83** breaks contact stopping motor **74** depending on the net head at any given time.

Further modification of the control circuit is found in the incorporation of resistors **111** and **112** and variable resistors **113**, **114** and **115** for the balancing of the basic and biasing circuits to permit adjustments of the circuits to insure proper operation of the various components thereof and to provide a means for the addition of further predetermined biases on the blade angle. Interrupting contacts, as **116** and **117**, may be added for coordination of the electrical operations with the hydraulic-mechanical operation if necessary, as for example, to permit a time lag for the exertion of pressure through pipes **54** to effect a change of blade angle or for the effect of a change of blade angle to be realized as a change of speed of the generator. Interrupting contacts **116** and **117**, if used, may provide different ratios of time open to time closed to correspond to operating characteristics if blade angle increase or decrease operations are materially different.

In Fig. 4 there is illustrated a modified basic circuit to adjust blade angle responsive to changes in wicket gate opening. This modified circuit includes rheostats **72** and **76** and motor **74** for the same functions that those elements performed in the basic circuit shown in Fig. 2, but has substituted for relay **83** the elements about to be described. In addition to lines **80** and **81** connected to a D.C. supply, this modification includes lines **120** and **121** connected to an A.C. supply and between which is located the primary winding **122** of transformer **123**. Secondary winding **124** of the transformer has attached at each end thereof leads **125**, **126**, **127** and **128** to the windings of the sides of each of two saturable core reactors **129** and **130**. Leads **125** and **126** are connected to the same end of secondary winding **124** and to corresponding sides of saturable reactors **129** and **130** while leads **127** and **128** are attached to the other end of secondary winding **124** and the corresponding sides of reactors **129** and **130** opposite from those to which are attached leads **125** and **126**. Leads **131**, **132**, **133** and **134** each containing dry disc rectifiers are also connected to the exterior windings of the reactors and to motor **74** to provide electrical connection from each reactor to one field of the motor. Wire **135** connects motor **74** to the center of secondary winding **124** of transformer **123** to complete a circuit through each reactor and through each field of motor **74**.

Wire **136** serving the same purpose in this arrangement as does wire **82** in the system shown in Fig. 2, interconnects contact arms **71** and **75** of rheostats **72** and **76** and forms the central windings of both reactors **129** and **130** but travels in opposed directions through the two reactors. By this arrangement a substantially direct current is applied in equal quantities on each field of motor **74** when contact arms **71** and **75** are in balance positions and no current flow exists through wire **136**. However, unbalance of contact arms **71** and **75**, as by a movement of main cable **41**, will cause a direct current to flow through wire **136** and the central windings of the reactors. Because the central windings of reactors **129** and **130** are reversed, the flow of the same current through both will create opposite effects in each reactor by aiding the current flowing in the outer windings of one reactor and opposing the current flowing in the outer windings of the other reactor in the directions of the released rectified currents. This influence on the rectified currents will cause one field of motor **74** to dominate the other when a condition of unbalance exists and cause movement of motor **74** driving worm **73** to effect a change of blade angle and restore a balance of contact arms **71** and **75** which will bring the system to rest.

In Fig. 5 is shown a further modification of the basic blade angle control circuit of Fig. 2, wherein rotors of two master units **140** and **141** of a selsyn or other positioning device are substituted for rheostats **72** and **76**. The rotors of units **140** and **141** are connected to an A.C. supply while the field windings of stators of units **140** and **141** are connected to rotor and stator respectively of a third or receiver selsyn unit or differential device **142** as best illustrated in Fig. 6. The rotor of unit **142** carries shaft **143** to which is affixed movable contact arm **144** which may swing back and forth between contacts **145** and **146** as the rotor of unit **142** is caused to move. Each contact **145** and **146** is connected to a field of motor **74** by a wire **147** or **148**. Motor **74** and contact arm **144** are connected to a D.C. supply by wires **149** and **150** so that contact of contact arm **144** with either contact **145** or contact **146** will activate one field of motor **74** driving worm **73** in one direction or the other. Movement of pulley **48**, as by a movement of main cable **41**, will cause movement of the rotor of selsyn unit **141** setting up a flow of current in the armature which is out of balance with that created by unit **140** and cause a movement of the rotor of differential unit **142**, shaft **143** and contact arm **144** which is one-half the angular movement of the rotor of unit **141**. When sufficient movement of contact arm **144** to cause a contact with either contact **145** or **146** is accomplished, motor **74** is activated and drives worm **73**, gear **67**, links **66** and **65**, floating lever **63**, cable **68** and pulley **69** to cause the rotor of unit **140** to follow the rotor of unit **141** until a balance position is achieved causing contact arm **144** to swing to a neutral position stopping motor **74**. This latter movement is accompanied by a movement of blade angle as accomplished by the structure shown in Fig. 1 and previously described.

In Fig. 7 there is illustrated a further modification of the basic circuit illustrated in Fig. 2 to adjust blade angle responsive to changes in the wicket gate opening, wherein an electronic circuit including a tube rectifier and a different relay is substituted for the relay and switch circuit in the cross wire **82** of the Wheatstone Bridge as shown in Fig. 2 to permit operation of the system entirely from an A.C. source. In this modification, rheostats **72** and **76**, motor **74** and mechanical elements **41**, **48**, **63**, **65**, **66**, **67**, **68** and **69** perform the same functions as they do in the embodiment of Fig. 2. This modification differs from that of Fig. 2 by the incorporation of lines **151** and **152** connected to an A.C. supply into which

is placed primary winding **153** of power transformer **154** and other elements about to be described.

These other elements include secondary windings **155**, **156**, **157** and **158** of transformer **154**, of which secondary winding **155** suplies power to lines **180** and **181** which supply current to rheostats **72** and **76** comparable to lines **80** and **81** of Fig. 2. Wire **182** interconnecting rheostats **72** and **76** includes primary winding **159** of input transformer **160**. Secondary winding **161** of input transformer **160**, along with the secondary windings **156**, **157** and **158** of power transformer **154** furnish control impulses and power to various portions of an electronic circuit including the dual triode electronic tube **162** and relay **163** for the control of a switch in the relay to alternately energize the fields of motor **74**. The heater of tube **162** is energized by winding **156** of the power transformer **154**. A constant equal potential across the tube from the cathode to each plate or anode is furnished by secondary winding **158** of the power transformer.

One coil **169** or **170** of relay **163** is included in each plate circuit of the tubes so that operation of one anode circuit while the other is blocked will cause the corresponding coil of relay **163** to tilt rocker arm **171** closing contact **172** with either contact **173** or **174** activating the corresponding field of motor **74**. Control of the tube is effected by grids **166** and **167** in a grid circuit including secondary winding **161** of the input transformer **160**. A grid bias is introduced from secondary winding **157** of power transformer **154** by wire **168** to the middle of secondary winding **161** of input transformer **160** so that no additional currents resulting from the grid bias are induced across transformer **160**.

Unbalance of rheostat **76** with respect to rheostat **72**, as by a movement of main cable **41** in a manner previously explained, cause a flow of current across the Wheatstone bridge through wires **182** and winding **159** of transformer **160**. The direction of movement of contact arm **75** to cause an unbalance between the rheostats will determine the direction of the current, within any half cycle, induced thereby within the grid circuit and determine which anode circuit will become dominant. Motor **74** is installed in such manner that operation thereof as controlled by the Wheatstone bridge, tube circuits and relay will cause movement of the mechanical elements previously described to adjust the blade angle responsively to the signal received from cable **41** and to cause contact arm **71** of rheostat **72** to assume a new position of balance with rheostat **76**, thereby bringing the system to rest.

In all of the embodiments of the invention disclosed, primary control of the speed of a hydraulic turbine-driven generator is accomplished by a hydraulic-mechanical means to adjust the gate opening responsive to a governor monitoring the speed of the generator and by an electrical-hydraulic-mechanical means, mechanically responsive to movement of the gates to adjust the turbine blade angle to the most efficacious setting for the particular gate opening without limitation to linear relationships between blade angle and gate opening. All embodiments permit further modification by the addition of interrupting contacts and biasing resistances to fit the invention to the particular operating characteristics of a particular system, a feature necessary because of the individual nature of hydro-electric power units.

Having thus described my invention, what I claim as new and wish to secure by Letters Patent is:

1. A control system for a hydraulic turbine having adjustable gate openings and adjustable pitch blades, comprising electro-mechanical means responsive to the speed of the turbine for adjusting the gate openings; mechanical means connected to the adjustable pitch turbine blades for adjusting the pitch of the blades; normally balanced electrical circuit means interconnecting said electro-mechanical means and said mechanical means, said electrical circuit means including common current conducting

means connected between balanced components of said balanced electrical circuit means, said common current conducting means including reversible electromagnetic components for operating said mechanical means; and means for energizing the normally balanced electrical circuit means; said electro-mechanical means simultaneously adjusting the gate openings responsive to the speed of the turbine and unbalancing said normally balanced electrical circuit means, electrical unbalancing of the said normally balanced electrical circuit means producing an electrical energy flow through said common current conducting means and its electromagnetic components actuating said mechanical means for changing the pitch of the blades consistent with changes in gate openings, said common current conducting means also including means for applying an electrical bias to the electrical energy flowing through said electro-magnetic components for changing the pitch of the blades proportional to the net head of the propellant acting on the turbine.

2. The structure of claim 1, wherein said means for applying an electrical bias include a rectifier, means electro-magnetically coupling said rectifier to a variable resistor mechanically responsive to the net head acting on the turbine and a source of alternating potential whereby the electrical potential across said variable resistor proportional to the net head on the turbine is applied to said rectifier through said electromagnetic coupling means for biasing the electrical energy flowing in said common conducting means for actuating said reversible electromagnetic components operating said mechanical means for changing the pitch of the turbine blades.

3. The structure of claim 1 wherein the said normally balanced electrical circuit means includes a manually operated member for starting, operating, and stopping said reversible electro-magnetic means.

4. The structure of claim 2 wherein the said normally balanced electrical circuit means includes a manually operated member for starting, operating, and stopping said reversible electro-magnetic means.

5. A control system for a hydraulic turbine having adjustable gate openings and adjustable pitch turbine blades, comprising electro-mechanical means operatively connected to the turbine and gates for actuation by the turbine and responsive to the speed thereof for adjusting the gate openings, mechanical means connected to the adjustable pitch turbine blades for adjusting the pitch of the blades, current limiting components interconnected as normally balanced electrical circuit means and interconnecting said electro-mechanical means and said mechanical means, said electro-mechanical and said mechanical means independently adjusting said current limiting components producing an unbalance in said normally balanced electrical circuit means, said electrical circuit means including common current conducting means connected between said current limiting components of said balanced electrical circuit means, said common current conducting means including reversible electromagnetic components actuatable upon unbalance of said normally balanced electrical circuit means for operating said mechanical means to vary the pitch of said adjustable pitch turbine blades proportionally to the independent adjustment of said current limiting components by said electro-mechanical and mechanical means for producing the unbalance of said normally balanced electrical circuit means, and means for energizing the normally balanced electrical circuit means, said electro-mechanical means simultaneously adjusting the gate openings responsive to the speed of the turbine and unbalancing said normally balanced electrical circuit means, electrical unbalancing of the said normally balanced electrical circuit means producing an electrical energy flow through said common current conducting means and its electromagnetic components actuating said mechanical means for changing the pitch of the blades consistent with changes in gate openings, said common current conducting means also includ-

ing means for applying an electrical bias to the electrical energy flowing through said electromagnetic components for changing the pitch of the blades proportional to the net head of the propellant acting on the turbine.

6. A control system for a hydraulic turbine having adjustable gate openings, adjustable pitch blades and variable net head constituting the operating variables of the turbine, comprising electro-mechanical means operatively connected for actuation by the turbine and responsive to the speed of the turbine for adjusting a first of said operating variables, mechanical means operatively connected for actuation by the turbine for adjusting a second of said operating variables, current limiting components interconnected as a normally balanced electrical circuit means, said electro-mechanical and said mechanical means interconnected by said normally balanced electrical circuit means for independent adjustment of said current limiting components producing an unbalance in said normally balanced electrical circuit means, current conducting means providing a common connection between said current limiting components of said balanced electrical circuit means and including reversible electromagnetic components actuatable upon unbalance of said normally balanced electrical circuit means for operating said mechanical means to vary said second of said operating variables proportional to the independent adjustment of said current limiting components by said electro-mechanical and mechanical means producing the unbalance of said normally balanced electrical circuit means, and means for energizing the normally balanced electrical circuit means, said common current conducting means also including means for applying an electrical bias to the electrical energy flowing through said electromagnetic components for adjusting the second one of said operating variables proportional to a third one of said operating variables.

7. A control system for a hydraulic turbine having adjustable gate openings and adjustable pitch blades comprising means for adjusting the gate openings responsively to the speed of the turbine, and self balancing electro-mechanical means for adjusting the blade pitch responsively to adjustment of the gate openings by said means for adjusting the gate openings wherein said self balancing electro-mechanical means includes an energized electrical balancing circuit including variable electrical balancing components for the self balancing of the electro-mechanical means responsive to gate and blade settings, in combination with an energized continuously variable electrical biasing circuit connected to said balancing circuit for introducing a biasing current into said balancing circuit proportional to the net head of the turbine propellant, said biasing circuit including a current controlling component attached to net head measuring means for varying the current in said biasing circuit and said balancing circuit continuously proportional to the net head and continuously responsive to any degree of fluctuations of net head.

8. Control apparatus for a hydraulic turbine connected to an electrical generator, the turbine having adjustable gate openings, adjustable pitch blades and a blade operating rod attached to the adjustable pitch blades for adjusting the pitch of the blades, said control apparatus comprising a plurality of interconnected control systems for maintaining optimum operation of the hydraulic turbine under varying load conditions on the generator, a first one of said systems including electrical drive means connected to said generator and responsive to variations in load conditions on the generator and mechanical linkage components actuated by said electrical drive means for adjusting gate openings on the hydraulic turbine, a second one of said systems including normally balanced linkage means connected to the blade operating rod for adjusting the pitch of the blades, normally balanced electrical components mechanically interconnecting the mechanical linkage components of said first one of said systems and said normally balanced linkage means, electrically driven means mechanically connected to said normally balanced linkage means and electrically actuated circuit control means constituting an interconnection for flow of potential output between said normally balanced electrical components responsive to potential differences produced upon unbalance of said normally balanced electrical components by variations in load on the generator, said electrically actuated circuit control means connected intermediate the output of said normally balanced electrical components and said electrically driven means for controlling said electrically driven means for adjusting the pitch of the blades through the blade operating rod to obtain optimum operating conditions of the hydraulic turbine for varying load conditions on the generator.

9. Control apparatus for a hydraulic turbine connected to an electrical generator, the turbine having adjustable gate openings, adjustable pitch blades and a blade operating rod attached to the adjustable pitch blades for adjusting the pitch of the blades, said control apparatus comprising a plurality of interconnected control systems for maintaining optimum operation of the hydraulic turbine under varying load conditions on the generator, a first one of said systems including electrical drive means connected to said generator and responsive to variations in load conditions on the generator and mechanical linkage components actuated by said electrical drive means for adjusting gate openings on the hydraulic turbine, a second one of said systems including normally balanced linkage means connected to the blade operating rod for adjusting the pitch of the blades, normally balanced electrical components mechanically interconnecting the mechanical linkage components of said first one of said systems and said normally balanced linkage means, electrically driven means for adjusting the pitch of the blades, said electrically driven means mechanically connected to said normally balanced linkage means, a manually operated member for starting, operating and stopping said electrically driven means and electrically actuated circuit control means constituting an interconnection for flow of potential output between said normally balanced electrical components responsive to potential differences produced upon unbalance of said normally balanced electrical components by variations in load on the generator, said electrically actuated circuit control means connected intermediate the output of said normally balanced electrical components and said electrically driven means for controlling said electrically driven means for adjusting the pitch of the blades through the blade operating rod to obtain optimum operating conditions of the hydraulic turbine for varying load conditions on the generator.

10. Control apparatus as recited in claim 8 wherein said electrically actuated circuit control means comprises a reversible relay.

11. Control apparatus as recited in claim 8 wherein said electrically actuated circuit control means comprises an even number of saturable core reactors, each reactor having a central direct current winding connected to the output of said normally balanced electrical components and alternating current windings connected to a source of alternating potential, said alternating current windings being connected through rectifying means to said electrically driven means.

12. Control apparatus as recited in claim 8 wherein said normally balanced electrical components comprise a first and second mechanically operated rheostat arranged in parallel across a source of electricity and wherein the contact arms of said first and second rheostats are interconnected through said electrically actuated circuit control means to form a Wheatstone bridge, said first rheostat being connected for operation thereof to the mechanical linkage components of said first one of said systems movable upon actuation of said electrical drive means to adjust gate openings on the hydraulic turbine responsive to variation of load on the generator, said second rheostat being connected for operation thereof to said normally balanced linkage means connected to the blade

operating rod for adjusting the pitch of the blades and being movable upon actuation of said electrically driven means by said electrically actuated circuit control means responsive to unbalance of said first and second rheostats produced by variation of said first rheostat from a balanced condition by said electrical drive means responsive to variation of load on the generator.

13. Control apparatus as recited in claim 8 wherein said electrically actuated circuit control means comprises electron tube means transformer coupled in the output of said normally balanced electrical components and selective circuit closing means connected in the output of said electron tube means and to said electrically driven means.

14. Control apparatus as recited in claim 8 wherein said electrically actuated circuit control means comprises a first selsyn electrically connected to an alternating electrical energizing source and to said normally balanced linkage means, a second selsyn connected to said electrical energizing source and to said mechanical linkage components of said first one of said systems, a third selsyn connected to said first and second selsyns and actuated responsive to relative movement between said first and second selsyns, and reversible electrical contactor means mechanically connected to said third selsyn and electrically connected to said electrically driven means and a direct current energizing source connected to said electrical contactor means and said electrically driven means.

15. An automatic control system for hydraulic turbines having adjustable gate openings and variable pitch blades comprising a first variable operating means responsive to changes in turbine loads, and a second variable operating means coacting with said first variable operating means in predetermined relation and responsive to changes in said first variable operating means, said first variable operating means including a first variable mechanical-electrical control means mechanically connected to the remainder of said first variable operating means and said second variable operating means including a second variable mechanical-electrical control means mechanically connected to the remainder of said second variable operating means, normally balanced electrical circuit means electrically interconnecting said first and second variable mechanical-electrical control means and having a common current conducting connection including electrically actuated components connected to said second variable operating means, means including the first variable mechanical-electrical control means for unbalancing said normally balanced electrical circuit means responsive to changes in gate openings, and a biasing circuit electrically coupled to said common current conducting means and including means responsive to a third variable affecting the operation of the turbine and effective to vary the predetermined relation between said first and second variable operating means, said third variable being directly connected to net head measuring means so as to vary proportional to the net head of the propellant acting on the turbine, whereby changes in the third variable biases the unbalance in said normally balanced electrical circuit produced by variations in the predetermined relation between said first and second variable operating means causing said electrically actuated components to be energized for operating the second variable operating means.

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