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GENERATOR-MOTOR FOR HATANAGI PUMPING-UP POWER STATION, CHUBU ELECTRIC POWER CO., INC.

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I. PREFACE

In Japan, recentry more and more hydraulic power plants are being installed in combination with thermal equipment in the so-called thermo-hydraulic system, in which the former handles the base load while the latter is used for the peak load. The combined power generation system usually takes the form of pumping-up stations, in which thermal power plant in slack midnight hours is utilized to pump up water into the reservoir to provide for peak loads.

Our Company is one of the first makers in the development for pumping-up power equipment, manufacturing such as pole change type synchronous machine, and consequently we are now in the condition for manufacturing of most adequate equipment in conformity with every sorts of projects for hydraulic condition and working condition. Generator-motor for the Hatanagi No. 1 pumping-up power station, Chubu Electric Power Co., Inc. now completed was the synchronous machine of normal construction, as the project had not requested pole change type synchronous machine especially. Nevertheless, for this machine as the pumping-up equipment, the greatest caution was taken in its design and manufacture, and this machine has numerous special characters, and at field test, excellent result was obtained more than our expectation, so we will report its contents and test results for your reference who has the interest for developing such pumping-up power station.

Upon the project of this generator-motor at the power station, special care was taken how we can start this machine quickly and surely without any large disturbance to the line system. For motor start at pumping-up power station, there are three difficult conditions. The first is, the machine has very large GD^2 enough to limit speed rise in a certain value when running as water-turbine, consequently heat loss induced in damper winding increases during acceleration and critical slip enough to pull-in is being small. The second is, motor input has a relatively large weight for system capacity as the purpose of pumping-up power generation is naturally to adjust power demand of system, consequently start kVA must be suppressed extremely as the shock caused by start kVA could not be neglected. The third is, motor impedance must be small for the sake of stability for generator operation, moreover start kVA could not be suppressed by increasing its self impedance as in the case of normal synchronous motor, consequently start kVA must be suppressed by any other means.

In order to solving these difficult points, auxiliary starting equipment must be skillfully utilized and thus suppressed start kVA must effectively be used.

In this machine, the latest techniques have been gathered, such as magnetic thrust bearing to reduce counter torque at start, reduced voltage part winding start, and phase detection quick-response excitation at full voltage synchronization, consequently motor was started surely limiting the start current below half of rated value. In the following, description will be made with the starting problems as its center.

II. RATING AND CONSTRUCTION

This power station is the pumping-up power station, in which peak load operation in the day time and pumping-up operation in slack midnight are being made mainly with 60 c/s, but as the 50 c/s operation at water-turbine operation may be occasionally requested, the machine is being designed for double frequency generator. As the on-load tap changer is equipped to the main transformer, the rated voltage of this machine is not changed particularly for motor operation. When it is operated at 50 c/s, the rated voltage is lowered to the reasonable value based upon the specification of 60 c/s operation and high power factor is being given.

Table 1 shows the specification of this machine.

As this machine is to be coupled with pump-turbine, it has various special features comparing with normal generator not only electrically but also mechanically. Further the capacity of this machine is the biggest one in our country as pumping-up generator-motor now in use.

Sectional view of this machine is shown in *Fig. 1*,

Table 1 **Specification of generator-motor**

	Generator rating		Motor rating	Exciter
Output	58,800 kVA	49,000 kVA	54,500 kW	330 kW
Voltage	11,000 V	10,000 V	11,000 V	440 V
Current	3,085 A	2,825 A	3,085 A	750 A
Frequency	60 c/s	50 c/s	60 c/s	—
Power factor	0.85	0.9	0.95	—
Speed	200 rpm	166.7 rpm	200 rpm	200/166.7 rpm
Inertia constant	8.6 kWs/kVA (4,600 t-m^2)			
Type	Vertical shaft self ventilating and recirculating type, salient pole revolving field type			

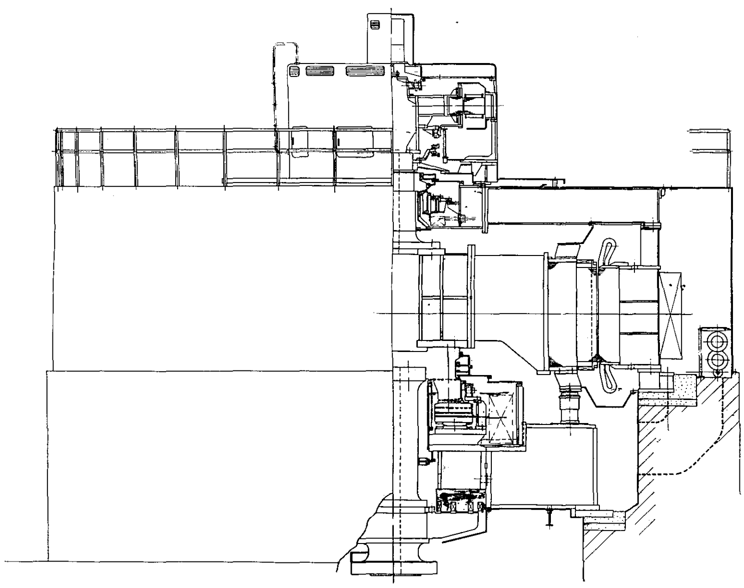

Fig. 1 Section of 58,800 kVA/54,500 kW generator-motor

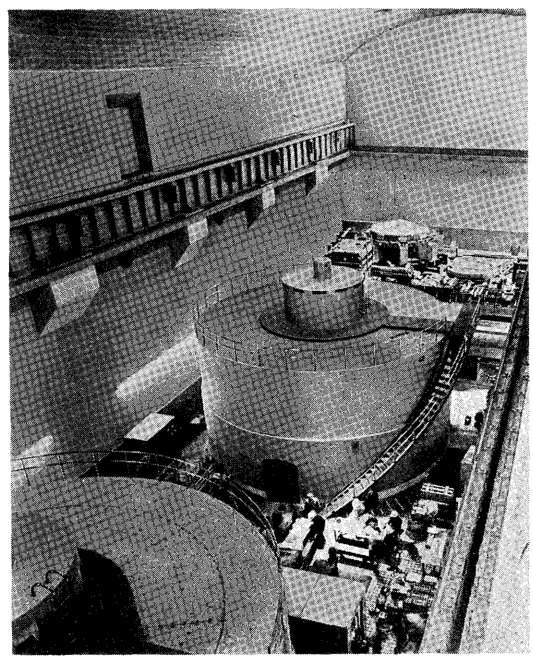

Fig. 2 Outer view of generator-motor

and it is high stabilized semi-umbrella type construction having the thrust bearing at lower bracket and guide bearing at upper and lower brackets. Exciter, tachometer dynamo and generator for pendulum motor are being installed upon the upper part of main body. *Fig. 2* shows its outer view.

Stator frame is 8.1 m in outer diameter, 2.2 m in height, made of steel plate welded construction and is divided to 8 parts for the requirement of transportation. Stator winding is made of one turn Gitter coil and treated with F resin insulation.

Upper and lower bracket are made of steel plate welded construction. Upper bracket consists of 8 arms and ring part having guide bearing oil basin in its center. Lower bracket is the construction of 8 assembled arms owing to the severe transport limit and 2 part of thrust oil basin, and these are fitted to center ring part of one-body construction which receives thrust load directly. Stationary part of magnetic thrust bearing is welded to lower part of centering and new construction has been adopted to shorten the vertical space and to strengthen the lower bracket effectively very much.

Upper guide bearing is being installed in the upper bracket oil basin and is one-body cylindrical bearing made of steel plate. We made an experiment on the effective shape of oil groove for rubrication and cooling about these reversible bearing, and confirmed that the shape of oil groove had not so much influence upon the characteristics of bearing, so that vertical groove was adopted finally.

Lower guide bearing made of steel plate is installed in the lower bracket oil basin and fitted on the outer surface of thrust collar. Bearing diameter is large size exceeding 2 m, and pivoted pads of ten odd numbers, endurable for heat expansion and easy for assembling and dismantling. For these segment pads, fitted on the bearing base system was adopted as usual, but full study for heat expansion was made and careful caution was paid for bearing clearance and for the segment fitting system. Further, upward thrust bearing is provided at the lower part of this bearing against the accidental lift of rotor.

Rotor weighs 239 t and its stress is being designed to have a safety factor more than 1.5 for yield point. Pole core is formed laminating with 1.6 mm thickness steel plate of high strength and fitted in the rotor yoke by dove tail key.

Field winding is made of F resin insulation coils, is inserted in the pole body and fitted at pole core, giving the adequate preheating and pressing, considering the centrifugal force and temperature rise which may be occured during running, therefore it is the construction which can prevent the deformation of coil and insulation due to heat expansion and centrifugal force during operation.

Rotor is formed laminating with 3.2 mm thickness steel plate of high strength punched in fan-shape and is made as one body strongly by reamer bolts. Shrinkage fit is being adopted as usual, but full consideration was paid, as it is reversible, for the construction of key between yoke and spider which is important for transmission of torque and also for the interference of shrinkage. Needless to say, caution was paid for the ventilating fan fitted on the rotor as the rotation is reversible.

Steel plate welded construction was adopted for both the rotor spider and the boss part, and rotor spider is our special construction of skin stress type having 6 arms, head part of each arm being divided into two. *Fig. 3* shows the construction of rotor.

Rotor is consisted from 4 parts, i.e. upper shaft, spider boss, thrust collar skirt and lower shaft, and these are made as one body using radial round pin and bolt mutually strong enough. Especially, the constructions, between spider boss and thrust collar and also between thrust collar skirt and lower shaft, are quite important for the powerful transmission of reversible torque, so that each constructions was decided after carefull investigation and is the quite stable construction now we believe.

On the other hand, crane capacity is reduced and lifting height is shortened owing to the each parts can be lifted each other when dismantled. It is well known, displacement of shaft center and balance have the large influence upon the rotating machine. Notwithstanding of adoption of part shaft, we can limit the shaft distortion below 2/100 mm even at the field adjustment of shaft distortion, owing to our high machining accuracy and carefull assembling works. Also, in our factory test for run away speed, we comfirmed that the strength of each parts, vibration, shaft distortion and temperature rise of bearing are nearly the same value and quite safety as we expected.

Damper winding receives the severe thermal stress during motor starting, so special cautions was paid for its construction.

As can be seen from *Fig. 4*, bars of special shape and material are inserted into slots of core, both ends of bar are soldered with end-ring which is parted at each pole, flexible connecting plates are used between each pole portion, thus one ring is being completed. In this case, adequate allowance is being secured for the space between slot and bar, also at fitting part between end ring and core end plate, so that free movement due to the thermal expansion of

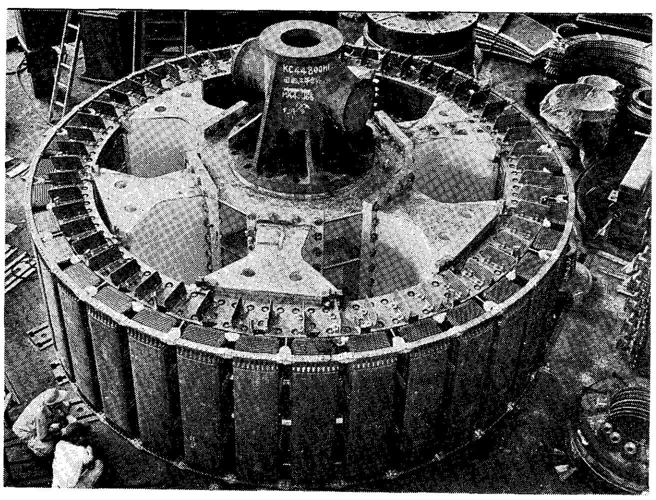

Fig. 3 Complete rotor of generating-motor

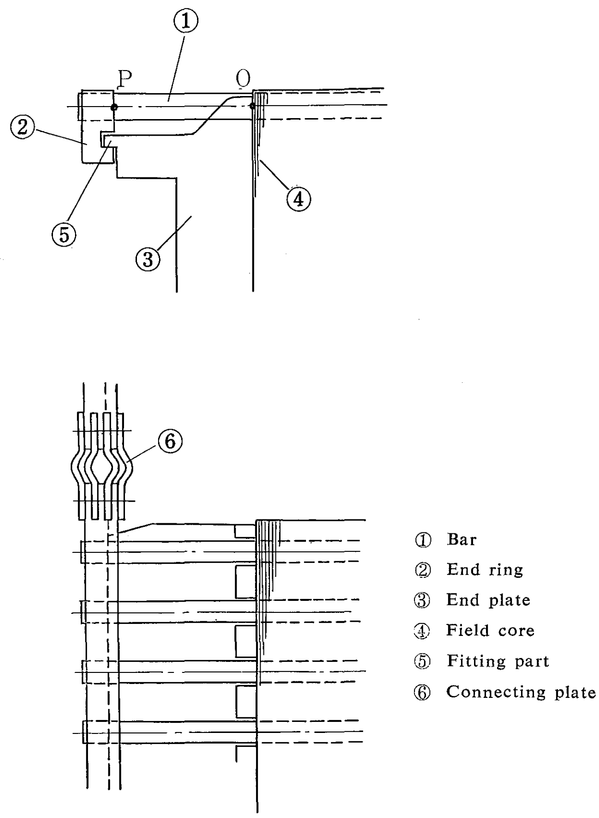

Fig. 4 Construction of damper winding

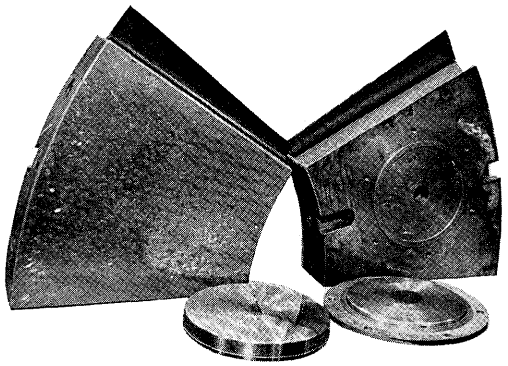

Fig. 5 Thrust bearing

bars at shaft direction can be allowed. The connecting plates for end ring are of flexible construction, having large curve at middle portion. The connecting plates are made of copper alloy, having superior thermal characteristics and high fatigue strength. Also curvature at the curved portion is so large and thickness is enough thin that the connecting plate can be safely withstood even against the frequent repeat of start.

The construction for this reversible type thrust bearing is different from one directional type. As well known at one directional bearing, the pivoted point of pad is of some eccentric from the middle point towards moving direction, where as at reversible type the centrally pivoted type is used as shown at *Fig. 5*. Load capacity at centrally pivoted type bearing is considered zero from the simple theory in which viscosity of oil is constant between outlet and inlet, but it is also known that considerable load capacity exists at actual operation. Regarding how to increase this load capacity and expect the more safe operation, many researches are being made for the shape of bearing surface such as the convex surface, now our Company adopted corner off shape sloped at both edges of inlet and outlet of oil, so that oil is being guided effectively and formation of oil film is being helped. Concerning how much the corner should be taken off, we decided its adequate dimension by experiment, etc.

Regarding the surface pressure of bearing, we adopted some lower value than usual one, considering that load capacity at reversible type is smaller than that of unidirectional type. Thrust load of this machine is being designed endurable for about 500 t, but at actual operation, using the magnetic thrust bearing, the actual thrust is near 200 t owing to almost all weight of rotating part should be lifted, thus practically the machine operates with much allowance for thrust load. The pivoting method of this thrust bearing is our standard type in which two disc springs are being combined as elastic pivot. Care must be taken at assembling of central pivot type bearing so as to minimize the height variety of pads on account of uniform load balance for each pad can be obtained. Our Company, owing to the merit for simple construction of thrust bearing including the spring, further making the severe inspection for each part and spring contract, on the other hand using high assembling technic for horizontal leveling of bracket and for adjustment of shaft distortion, conceives that the adjustment after assembling is quite needless. The bearing temperature rise at our

***Table 2* Home-test result (60 c/s running)**

Efficiency (100% load)	98.1 % (1.0 pf)		97.6 % (0.85 pf)	
Short-circuit ratio	1.0			
Temperature rise	Startor winding 52 °C		Rotor winding 50° C	
	Bearing temperature rise (above cooling water temperature)		Magnetic bearing, excited	Magnetic bearing, no excited
		Rotate as generator	24.8 °C	33.4 °C
		Rotate as motor	24.3 °C	32.3 °C
Each kind of impedance	x_d	100 %	x_q	67.5%
	x_d'	38.7%	—	—
	x_d''	26 %	x_q''	24.6%
	x_2	25.5%	x_0	13.4%
Start torque (single star 50% voltage)	21.9 t-m²			
Start kVA (single star full voltage)	29.8 MVA			
Pull-in torque (single star 50% voltage)	18.1 t-m²			
Distortion factor	1 %			
Exciter ceiling voltage	987 V			
Exciter voltage-up gradient	2,435 V/sec			

factory test can be seen at *Table 2* and quite safe operation for both direction have now being continued at field.

Eight pieces of air brake were installed at lower bracket arm, begin to operate at 30% speed of rated one and stop the machine within about 50 sec. after beginning to stop. Because start and stop motion is frequent, two limit switches for acknowledge the condition of start and for alarm the limit of lining abrasion are being provided at each brake for the sake of safe operation. Special care was being taken at selection for material of brake ring and lining. The lining is made of resin mold based with asbestos, and to improve its sliding characteristics powdered metal is mixed in the lining, and further, regarding its heat treatment the quite new high grade process was taken. The abrasion of this new product, by our test piece is below 1/5 of the usual old one operating in other power station. By development in lining material and increase in lining thickness, further with the improvement of fitting method to the base plate, we increased widely the endurable times. Further, dust collecting equipment is being provided against the scattering of lining powder into the machine, as brake operates many times according to the frequent start and stop motion.

III. FACTORY TEST

In the factory test of this machine, test as motor was made as many as possible besides general test as generator. The results gathered can be seen at *Table 2*. The efficiency is the value in which the bearing loss was reduced by magnetic thrust bearing and higher than the usual generator.

Further, to our interest, temperature rise of bearing is lowered widely about 8°C by the magnetic thrust bearing system. This temperature lowering is an important merit concerning the reliability of bearing and the life of lubricating oil, thus can be considered as the extra big merit of magnetic thrust bearing. For this machine, special care was taken not to injure the stability as generator even though the machine must have motor characteristics, thus each kind of impedance is standard value as water turbine generator and is the satisfactory reliable figures contributable for stability of system when runs as generator. Torque characteristics and current figures as motor are obtained from lock test at reduced voltage and induction motor characteristic test, and these figures coincide quite well with those tested at field as stated in the following. Exciter is excited using OH type compound exciting apparatus, so that the same quick response characteristics was displaid quite well at actual operation. Besides, the machine has endured for run away test of 330 rpm for 1 min. without any vibration or other defects, further the winding, to be affected with shock on each motor starts, is made of F resin insulation and showed its excellency by its tan δ gradient in tan δ–V characteristic curve being only 0.04%/kV which shows quantity of void.

IV. MOTOR CHARACTERISTICS AND FIELD TESTS

1. Selection for Starting Method

As for the motor starting method for pumping-up power station, there are two methods, one is the indirect method using the starting motor or the direct-coupled exciter specially designed to get large starting torque, another is the self start method.

The former method was always used to start synchronous condenser, frequency changer and large capacity motor in the former time, and capacity of starting motor is sufficient below 5% of main motor. This method is most suitable in case of relatively small source capacity compared with main motor output, but has demerit such as additional machine should be coupled or DC source being secured.

Recently the power line to be used for pumping-up power generation has been giantic enlarged, so that increase at start current does not affect so much trouble against power line when self start method were adopted as induction motor. Thus this most economical self start method has a tendency to be adopted for start of a large capacity motor, and now the Hatanagi No. 1 Power Station adopted this method. In this respect, this power station was the test case for self start of large capacity machine in our country. Moreover the reduced frequency start method, such as often practised at turbo-generator, can be effected if the number of generator-motor at this power station increased more than three units.

2. Method to Reduce Starting Current

For the self start method which was adopted and may be used broadly hereafter at the pumping-up power station, the procedure to reduce the line disturbance must be considered, securing the necessary torque characteristics, so that various method how to reduce the starting current have been considered. Generally speaking, for motor torque of pump, starting torque is small and pull-in torque is large. But, in the case of vertical shaft machine, the counter torque at instant of start is not always small owing to the speciality of bearing. At the step of pull in, quite enough accelarated, pull-in is very difficult if no means being applied, on account of counter torque is 100% and GD^2 is large. Therefore, to suppress rush current at start, the reducing equipment for counter torque is always necessary and suppress limit of current depends upon the reducing degree of counter torque.

In the case of magnetic thrust bearing now used for reducing the counter torque at start instant, counter torque can be reduced nearly zero, and moreover excitation is adjustable, so that its action is reliable and there is no limit for current suppress owing to starting torque. The limit of current suppress is decided by the magnitude of counter torque at pull-in. For reducing counter torque near synchronous speed at this Francis-type water turbine, it is the only way to run the impeller in the air, and we have succeeded in reducing counter torque sufficiently in the same way as described later.

Concerning the suppress method for starting current, the following three methods are generally used, and considering various conditions one or more than two methods combined is adopted. In this machine, as we have succeeded in reducing counter torque remarkably, we could suppress starting current till about 50% of full load current most effectively and economically by adoption of half voltage start and part winding method. In the following, features for each starting method and reasons why we adopted above-mentioned combined method, will be explained.

1) Direct-On-Line Start

This starting method, connecting the motor terminal direct on the power line, is mainly applied at low speed motor in the quite small power station. If we start directly this generator-motor in the power station, start kilovolt-amperes is 400% (235 MVA) and starting torque is 50% of rated torque. In the above, torque and starting power are based on 58.8 MW 200 rpm and 58.8 MVA. This large starting current is, of course, unallowable value for this line system, and also starting torque is unnecessarily large, consequently starting impedance should be increased.

At generator-motor possibly small synchronous impedance is most desirable to enlarge steady-state stability, so that in project of large capacity machine the maximum impedance value is designated for line-system operation. In the synchronous machine only used as motor the starting impedance can be increased to enlarge the limit in which direct-on-line start can be attained, but in such case as generator-motor having opposite requirements for its impedance, the range for direct-on-line start is narrow and can be used only at small power station usually below 5 MVA.

2) Reactor Start

This starting method, line voltage is applied through the reactor, is often used in such load as pump, in which counter torque quickly increases following with speed up, and on the other hand voltage to motor also increases following with speed up, resulting smooth start can be obtained. But in pumping-up power station, in which current suppress is requested extremely, this method is not used on account of additional provision of reactor and also very low torque efficiency.

3) Compensator Start

In this starting method, reduced voltage of 30~80% is applied through the auto-transformer type compensator, then after accelerated near synchronous speed or after synchronization, full voltage is applied by change over switch. This method has high torque efficiency and can be adjusted to any desirable value, so that is being often adopted for self-start at rescent large capacity machine. As the 50% voltage tap of secondary winding (delta connection) at the main transformer can be relative easily drawn out from its construction, 50% voltage start is economical, using the main transformer as special type compensator start. When start by half voltage at this machine, starting current is 100% and starting torque is about 12%.

Generally, as above mentioned figures satisfies the requirement for pumping-up generator-motor, these are often adopted. In the case of the Hatanagi No. 1 Power Station, not satisfying at this figure, we succeeded in suppress start kilovolt-amperes below 50% (30 MVA) of rated value, reducing the counter torque extremely by using magnetic thrust bearing on one hand and furthermore adopting below mentioned part-winding start on the other hand.

4) Part-Winding Start

In this starting method, voltage is applied only to one circuit of armature winding devided to n parallel circuits, and both the starting current and the starting torque reduce to about $^1/_n$. This method is economical and effective as it is enough only to provide switch according to the number of parallel circuit. Regarding number of parallel circuit, there is a design limit according to number of pole, capacity and rated voltage. In the case of this machine, as it is double star connection, starting torque and current can be suppressed to 1/2.

Besides, these torque characteristics and torque efficiency varies widely according to the construction and material of damper winding. For example, by adopting special winding such as double cage type, deep slot type or inverse T type, torque efficiency is raised and can harmonize load characteristics with motor torque characteristic. It is not so advisable such complicated shape being taken to damper winding in the case severe mechanical requirement exist, that is, damper winding must be endurable for centrifugal force at run away speed and also for overheat at starting time due to large GD^2. In the case of this machine, we adopted the most simple shape having some deep slot effect, and looked for harmony of torque characteristics mainly from the material used.

3. Reducing Method for Counter Torque

(Reducing of starting torque by magnetic thrust bearing)

When it is desired the starting current be suppressed, the reducing device for counter torque is always necessary. Regarding counter torque come into question for pump load, two torques quite independent each other exist, i.e. torque at starting instant which is affected by the static friction coefficient at slip 1, and torque of impeller in fluid which increases proportionally to square of speed and becomes maximum at the instant of pull-in.

Torque at starting instant is mainly friction torque of thrust bearing, consists of average diameter of bearing segment, bearing load and static friction coefficient all multiplied each other. In the case of this machine the value reaches to 25% of rated torque. One method for reducing this counter torque is the oil pressure lift type start, in which high pressure oil is pressed by oil pump into the bearing segment and revolving disk. In this case minimum value of starting current must be decided with enough allowance from the reason that lifting oil pressure is high and friction coefficient itself has many ambiguous factors. On the contrary, in the case of our magnetic thrust bearing, starting current can be taken as minimum without any allowance, from the reason that the thrust load is directly reduced and furthermore exciting current can be adjusted. This machine starts at excitation so as the bearing load can be decreased to several percent of total static friction load, and even when the exciting current is lowered below 75% the machine can start by half voltage half winding start method at worst frictional condition. At actual test, the machine started at the instant of voltage supply and smoothly speed up without time delay, shock or vibration.

At the present test, when the magnetic thrust bearing being used, it was cleared up that the machine can start easily with enough allowance suppressing start kVA to about 50% of rated kVA, regardless to stop interval, variation of friction coefficient and voltage fluctuation of power line. For reducing the counter torque near synchronous speed, there is no means except the water around the impeller should be depressed by air and be rotated in the air till the motor synchronized parallel. This water level depression is made by compressed air, and counter torque varies considerably by water leakaged through the small space of guide vane. The annual progress, for the abrasion of guide vane and the counter torque, has influence upon start method itself and is the interesting and important items, yet as we have no such illustration, these change should be noticed hereafter. Needless to say, at the starting method which we adopted in this machine. start can be made always surely without any influence for increase of water leakage.

4. Field Test for Motor Operation

In the factory test, motor operational characteristics especially its starting characteristics can be hardly acknowledged fully due to our testing equipment and capacity of our power source. We could only take torque-speed characteristics from lock-test measured by low voltage supply and asynchronous speed test. For the full acknowledgment of motor operation, it must be depended upon the field test combined with actual load. So we endeavored especially in field test of motor operation, and confirmed the function at all steps for start, pull-in and full voltage synchronization.

Further, to check the future influence of water leakage which is considered coming from the abrasion of G.V. or the like, we tested the motor operation at water leakage openning the guide vane to a certain limit. But in this case are confirmed that motor runs normally overcoming its increase of counter torque due to water leakage. Though the relation between the artificial test and the actual leakage possible in pump operation is unknown, we thought when the actual leakage condition which requires repair, the noise caused by leakage may be nearly the same as those aroused by openning the G.V. artificially. So even when the water leakage increased, we can take necessary action. In the following, the field test results for motor start, pull-in, and full voltage synchronization will be explained.

1) Start

For the starting method of this machine we adopted combined method of half voltage start and the part winding start, so that start kVA of motor was quite effectively suppressed. At field test we adjusted the exciting current of magnetic thrust bearing at many

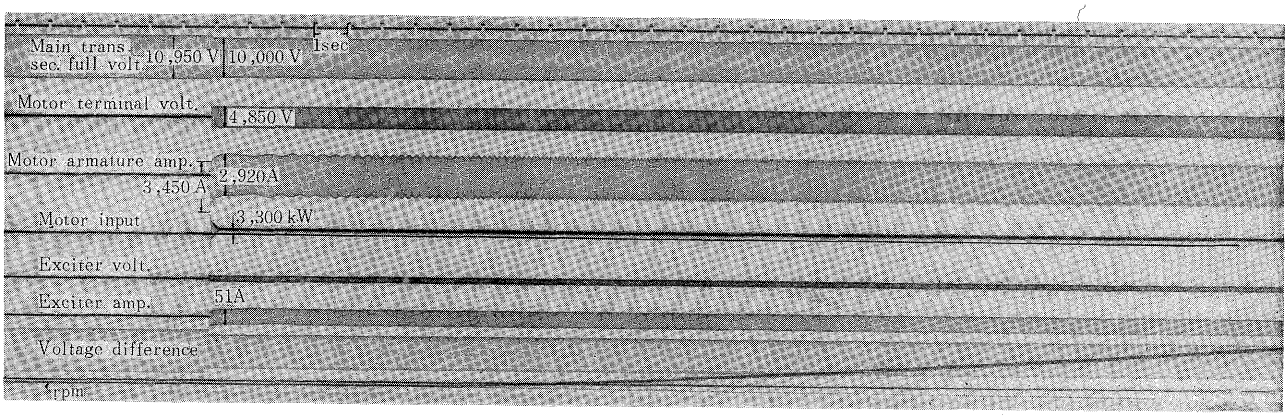

Fig. 6 Oscillogram of motor start step

values to change the condition of counter torque at start, and also we tested how stopping interval before start be influenced upon the counter torque of bearing at start. Even when the exciting current of magnetic thrust bearing was reduced near 75% of rated value, the motor rotated without delay at the instant of voltage supply. Stopping interval before start has influence upon the oil film of thrust bearing, and when stopped long period the bearing metal and thrust collar may make metalic contact, thus may causes the starting trouble of main motor. So we tested after long enough interval before start and confirmed the motor can start without any trouble. Further, following the increase of water leakage, counter torque at start may also increases, so we confirmed motor start can be done by half voltage part winding start at the artificial water leakage condition which may be considered maximum. *Fig. 6* is the oscillogram of motor start kVA at the instant of voltage supply. *Fig. 7* is the sumalized result for motor kVA, rpm, motor torque and time progress of terminal voltage, from the instant of start till near synchronous speed. Starting time is about 3 min. from the instant of voltage supply till maximum speed as induction motor. Applied voltage to motor dropped to 4,850 V by starting current from the voltage of 5,500 V before motor start. During start, motor start kVA is 25 MVA for about 1 min. and hereafter about 16 MVA being quite small.

Also to acknowledge the lowest limit of start when the voltage of power line dropped, we made starting test at 4,700 V before start which is 85.5% of normal half-voltage by adjusting the tap of LRA (load ratio adjuster) lowest at Oigawa Substation. In this case, the motor terminal voltage dropped till 4,200 V at the instant of voltage supply, but motor started with enough allowance. Further, for reference, half voltage double star winding start was made, voltage dropped to 4,700 V by starting current from the voltage 5,500 V before motor start. During start, motor start kVA is about 42 MVA for 70 sec. till minimum slip.

The temperature rise of damper winding must be considered as one of the problems by start, and full consideration was taken at the design step as stated before. The heat energy induced during acceleration of total moment of inertia ($GD^2 = 4{,}600$ t-m^2) reaches to 2.52×10^5 kW·s at every one starting. At field test we painted thermo-paint on each parts of damper winding and inspected properly. Finally after two consecutive starting test we confirmed temperature rise at end-ring of damper winding was remained near 70°C. Although we could not measure the temperature rise of bar in the middle of pole, but as the test result of end-ring was quite coincided with the designed data, we can expect the temperature at middle part might not exceed the designed temperature of 150°C.

2) Pull-in

Pull-in is influenced by synchronizing power, GD^2 of all revolving unit, motor slip when excitation applied and internal angle. Among these factors, motor slip varies widely by counter torque of pump and could not presume its value at the factory test, so we had a great concern about pull-in at our scheduled half voltage part winding start. But at the actual result, counter torque of pump coincided with our presumed figure, so we could have pull-in as in our schedule. *Fig. 8* is one of oscillogram for pull-in. Also motor internal angle at the step of pull-in was measured as can be seen at *Fig. 9*, and these results was figured on the phase plane as *Fig. 10*. Motor input at synchronous speed, when the guide vane of pump had fully closed, was about 1,450 kW and minimum slip which could reach to its condition was about 0.26%.

At artificial test of water leakage, counter torque of pump caused by water leakage increased suddenly correspondingly to a little openning of guide vane, and motor input at synchronous speed by the considered allowable limit of leakage increased to about 3,700 kW and could not pull in at the half voltage

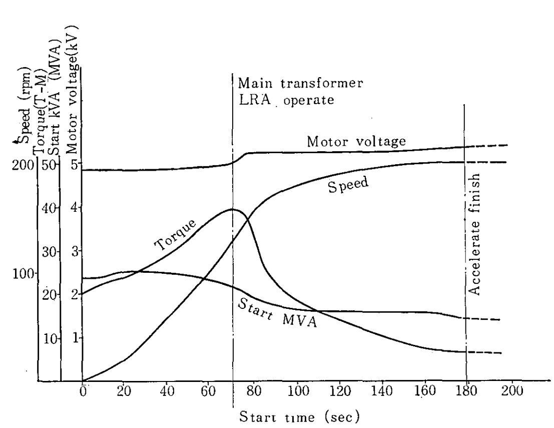

Fig. 7 Result of motor starting test

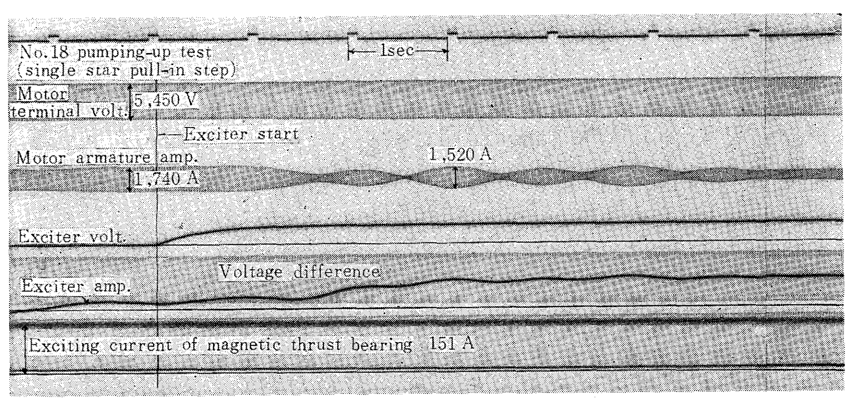

Fig. 8 Oscillogram of pull-in step

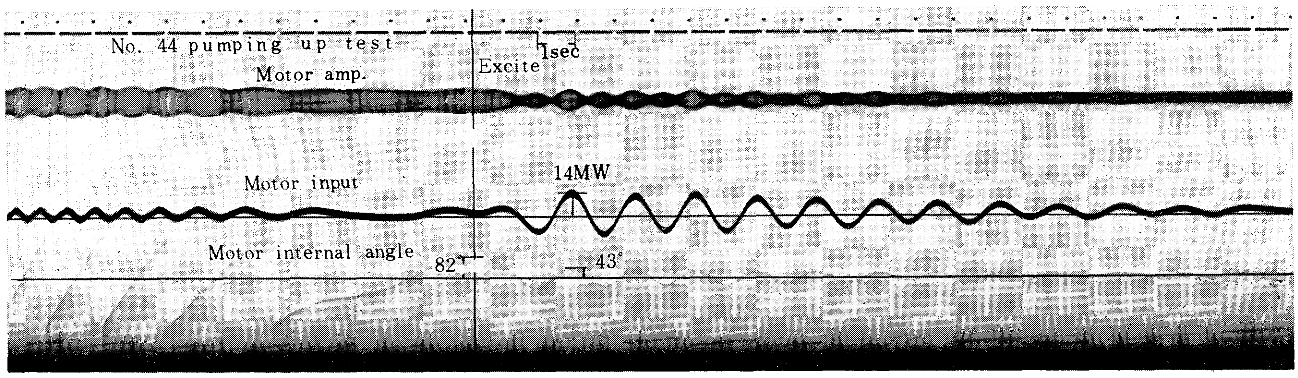

Fig. 9 Motor internal angle at pull-in step

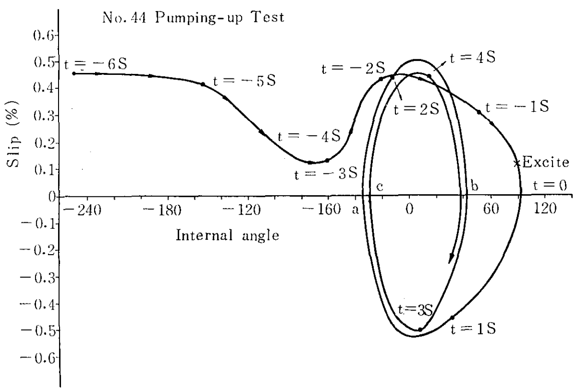

Fig. 10 Trajectory of pull-in step

part winding start method, but as described later control system for this machine was such schedule as, when a certain time elasped with pull-in delaying at half voltage part winding start condition, pull-in can be done by change over to double star connection, thus even at the above mentioned leakage condition pull-in could be easily excecuted by adopting double star connection.

3) Full Voltage Synchronization

Full voltage synchronization is made when a certain time elasped after pull-in at half voltage start, but also in this case various consideration was paid as detailed in the next paragraph to minimize the influence upon the system. Concerning the sequence, first the circuit breaker of half voltage side is opened, motor speed begins to decrease by load torque. Regarding the mutual connection between motor and main transformer, each motor terminal is to be connected to full voltage tap of main transformer lagging 60° in electric phase from that of half voltage, thus phase detector is so provided that circuit breaker of full voltage side can close when the induced voltage of motor came in phase with full voltage by lagging due to speed decreases.

Necessary time till the motor voltage comes in phase with that of full voltage after when half voltage is cut off, varies each time by influence of counter torque of pump, and time was measured every time of start at full closed condition of guide vane, consequently we confirmed that it varies at range of about 2.3 sec. to 1.2 sec. Therefore, merely to close the full voltage circuit breaker by time relay causes the transference of reactive power to line system, so that the adoption of phase detector is the necessary means to prevent the line disturbance. *Fig. 11* is one of the oscillogram showing full voltage synchro-

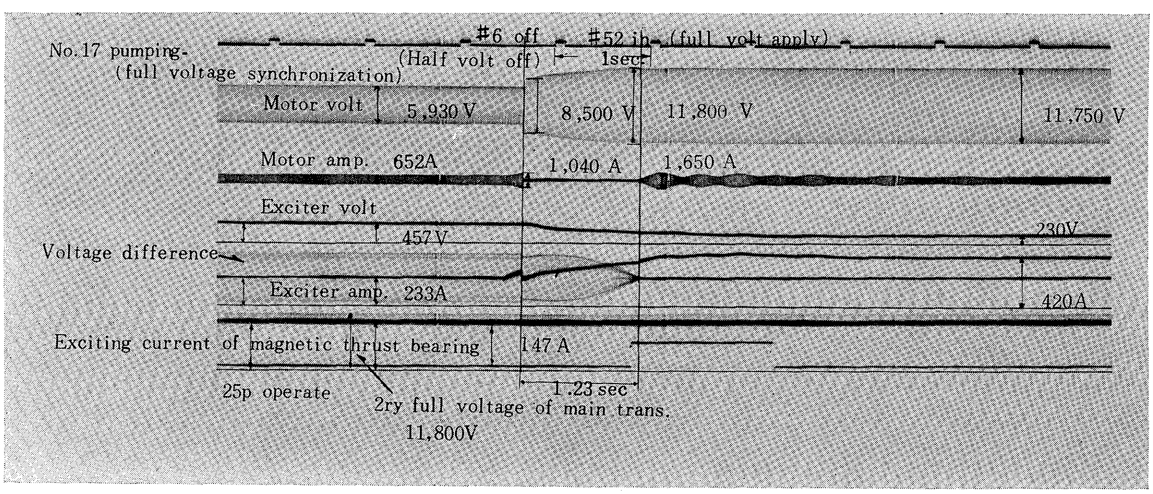

Fig. 11 Oscillogram of full voltage synchronization

nization. Voltage difference shown in *Fig. 11* is that composed of system voltage opposite to motor voltage, and as we can see at *Fig. 11* the full voltage circuit breaker was closed ideally when the voltage difference is zero, so that synchronizing current is quite small. In this example, pull-in was made at start condition of half voltage part winding and change over to double star winding was already made during the no voltage period before the full voltage circuit breaker close, so that pumping-up operation is quickly obtained as soon as the full voltage circuit breaker is closed.

Motor slip, when the full voltage circuit breaker is closed, can be derived as about 0.24% from the oscillogram showing the variation of internal angle during change over, and as the limit slip at full voltage pull-in is about 1%, so that full voltage pull-in can be made quite smoothly. The required time, in case of pump leakage increases and counter torque enlarges, in which the phase laggs 60° after the half voltage circuit breaker was opened, is below half of that in case of no leakage. Also in that case phase detector operated quite well and closing of full voltage circuit breaker was made at quite adequate time same as the example of *Fig. 11*. Further, motor voltage has recovered in this interval, thus motor starting current was suppressed in a small value.

V. CONTROL

This power station for pumping-up operation is connected in two ways through the main transformer of 58.8 MVA, 132∼168 kV/10.5 kV with LRA (Load Ratio Adjuster), one is directly to 270 kV line closely linking with Oigawa Substation, other is paralleled to 270 kV line and Oigawa 150 kV line at Oigawa Substation. As the starting time requires more than 1 min., in the former case the LRA at Oigawa Substation and in the latter case AVR also operate all combined with LRA of this power station, thus compensate the voltage drop due to starting current. Control system is one man control capable to watch and control at switch room, its single line diagram can be seen at *Fig. 12*.

Control system for generator operation is the same as usual water-turbine power station, so we will describe the control system for pumping-up operation. Starting is made in order as shown at *Fig. 13*.

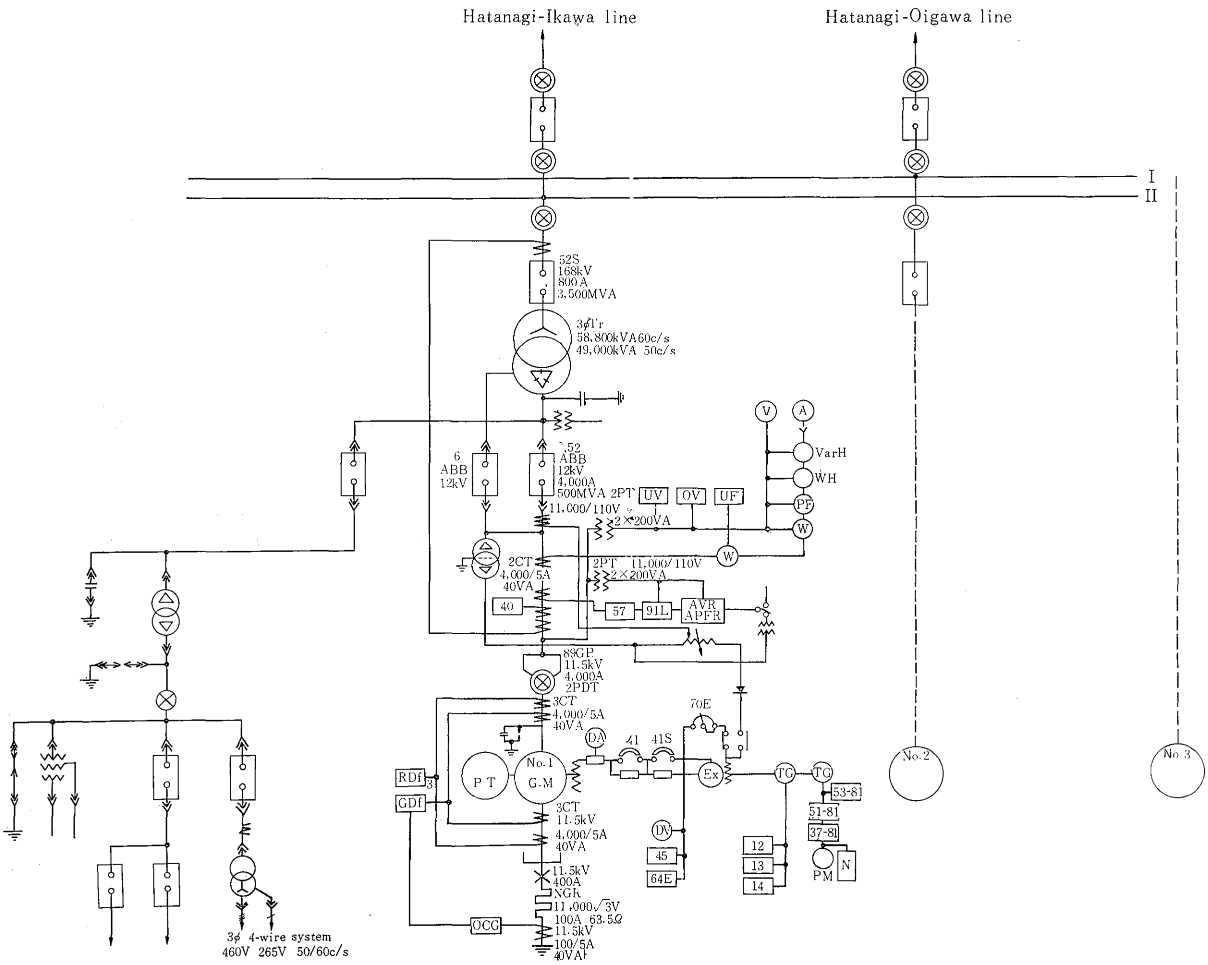

Fig. 12 Connection diagram of Hatanagi No. 1 P. S.

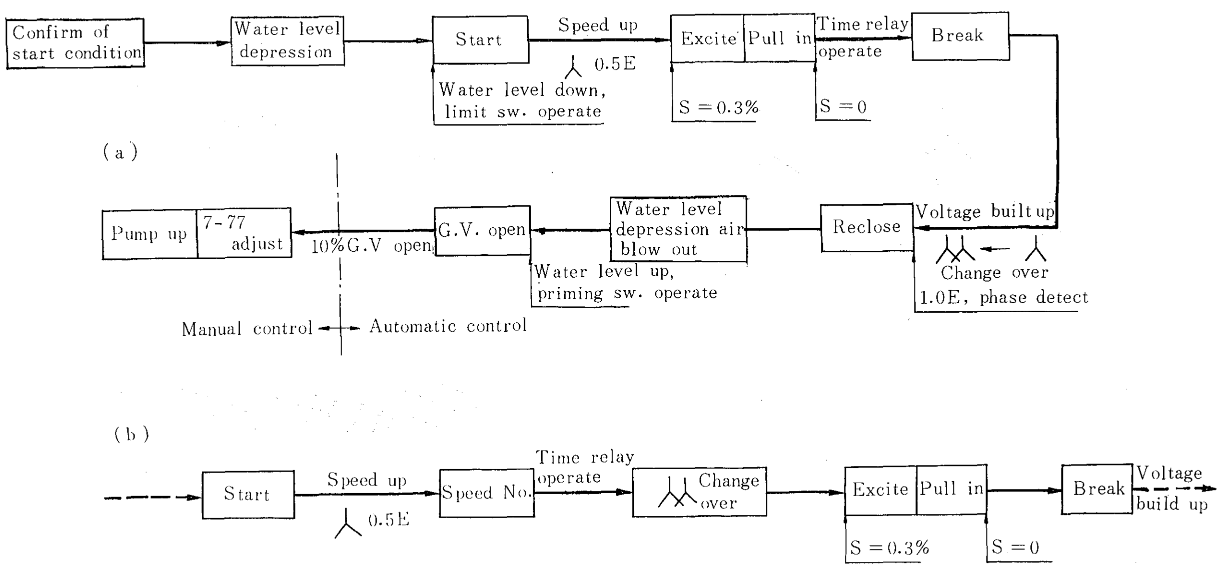

Fig. 13 **Sequence of events that take place during a normal start**

First, air bleed-off valve (valve M_1) " close ", water level in the pump is depressed. Lowering of water surface is confirmed by the operation of limit switch. Also, float switch is connected with compressor during start and always maintaines at water level of a certain range. For the condition of starting circuit breaker " on ", the following is added besides the common condition as water-turbine operation.

(1) Magnetic thrust bearing being excited
(2) Single star winding being obtained
(3) Magnetic field is short-circuited with starting resistance
(4) Water level depression is completed.
(5) Main valve open
(6) Secondary voltage of main transformer and voltage of half voltage tap are settled at a certain value
(7) Automatic synchronizer, automatic power factor controller " in "

Start can be made even when the excitation of magnetic thrust bearing is fairly smaller than the set current, the influence of voltage drop at starting time is nothing so serious. In this machine constant current is obtained by using saturable reactor for caution's sake, moreover set point can be changed continuously.

When start breaker is closed, it accelerates till the speed at which counter torque and induction motor torque balance, and slip becomes small till about 0.25% at the usual condition. But, when as it is, the machine synchronizes soon by reaction torque and power swing at next step of excite becomes large, so we settled slip relay so as excitation shall be made at a little large slip of 0.3%. When the final slip does not reach to 0.3% in case of counter torque increases by abrasion of G.V. or voltage drop, connection shall be changed to double star before synchronization. For this control, control circuit, automatically obtains double star connection, is being adopted at the condition in which the field circuit is not closed even when a definite time have been elasped exceeding a certain speed (No). The compound character is being given for the excitation source, and a part of it is taken from current transformer, so taking care not to be over excited during transient of start and pull-in, current transformer is put in only for full voltage circuit so that compound character has not be given at half voltage operation. Also field is adjusted to be always at minimum of motor V-curve by set of 90 R during half voltage operation, and after changed over to full voltage, power factor control is so used that reactive current to motor can be minimized.

Start breaker is opened after a definite time elasped after synchronization. Start resistor in series to field is short-circuited at the instant of breaker open. Exciter voltage at half voltage operation is near ceiling voltage owing to start resistor, and this voltage adds to the field of main motor by resistor short-circuit, thus terminal voltage of main motor is builded up to full voltage by usual operation of AVR.

Run breaker is closed at phase lagged 60° by motor speed decrease. Time required for phase lag of 60° varies widely by even a slight change of counter torque, thus time for breaker " close " can not catch by time relay. Therefore, close order is despatched at near 0.1 sec. to be in phase using phase detector. Phase detector usually detects the phase between the system voltage and the self terminal voltage, but in this case it is difficult to detect phase as voltage is changing its value. This time, instead of self terminal voltage, we adopted voltage of tachometer dynamo in which no. of poles and pole center coincided with that of main machine.

At the same time of run breaker " close ", M_1 valve opens, water level is depressed, and air is blown out. Water is leveled up, water level in pump becomes high, their priming switch operates, G.V. opens 10%.

It proceeds till above-mentioned step automatically by master control switch, but hereafter controlled manually by 7–77 till best gate opening and pumping-up operation begins.

Stop control is quite simple, at normal stop put 52 " open " and at the same time G.V. " close ", thus speed decreases. In this case field circuit is also opened at the same time. When speed decreased till 60 rpm, pneumatic mechanical brake operates automatically and is braked to stop. At normal stop, if main valve is not " close " position by master control switch, main valve remains open and can continue the next operation.

At emergency-stop, the sequence is same as normal-stop, and it differs only at the point that main valve necessarily automatically closed.

An example for pumping-up process by master control switch is shown at *Fig. 14*.

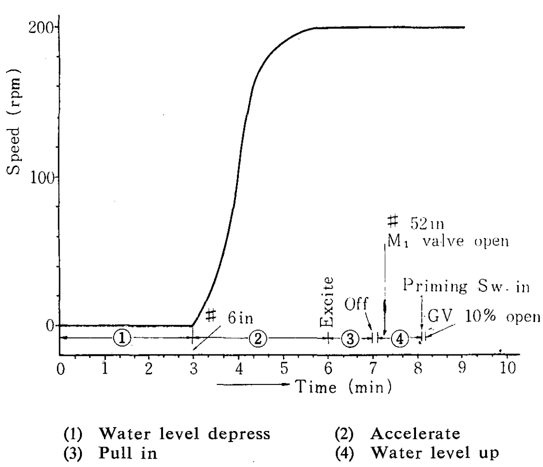

Fig. 14 Process of motor start

VI. CONCLUSION

This pumping-up power station is regarded to be a first record in our country as adopted a regularly large capacity pump-turbine. Our Company concentrated all the effort in design and manufacture before project design, basing on experimental data and model tests as well as through investigation in experienced matters.

But each result should be verified by field test. Fortunately by full understanding of user, careful test was made to our many thanks with so much time and labour for every kind of test considered all the case which may happen. Results obtained may contribute as the precious experience to whom concerns with pumping-up power station.

At present test of Francis type pump-turbine, start was possible suppressing starting current near half of rated capacity, and to our great fruits even when leakage increased remarkably start could be made surely if means for increase of motor torque were adopted for quite a short time before pull-in.

Finally we express our thanks to the authorities concerned of the Chubu Electric Power Co., Inc., the parties concerned of the Hatanagi Pumping-up Power Station and technical personnels co-operated with us for the present test.