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NEW CONTROL SYSTEMS FOR AC CRANE

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I. INTRODUCTION

Recently cranes have been directly coupled with parts supply, transport and assembly lines in steelworks, shipyards and machinery works and play an important role in industry. Therefore, there are increasing requirements for high lift, large capacities, high speeds and long spans. In accordance with these requirements, Fuji Electric has developed new synchronizing operation control systems and US control systems for AC cranes.

The synchronizing operation control system is used with long span overhead cranes, gantry cranes and multi-crab cranes. Since the difference in speeds among the motors is within one revolution with these control methods, yawing of the girders in prevented in the travelling of overhead cranes and hoist errors when multicrab cranes are hoisting long span materials and travelling simultaneously are negligible so that accuracy is high. Already 50 sets have been delivered and are operating well (*Fig. 1*).

The US control system is a new system for lowering control with automatic speed control by dynamic brake control. Compared with the conventional control systems which use thruster brake control or eddy current brake control, this system has shorter acceleration and retardation period and brake lining wear is reduced since the gross GD^2 of the motor shaft is lowered. In addition to ordinary lowering control, the US control system is highly effective in

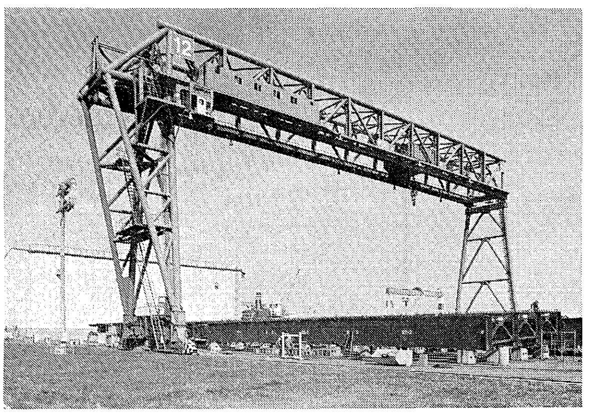


Fig. 1 50/25 t×50 m gantry crane (synchronizing operation for travelling)

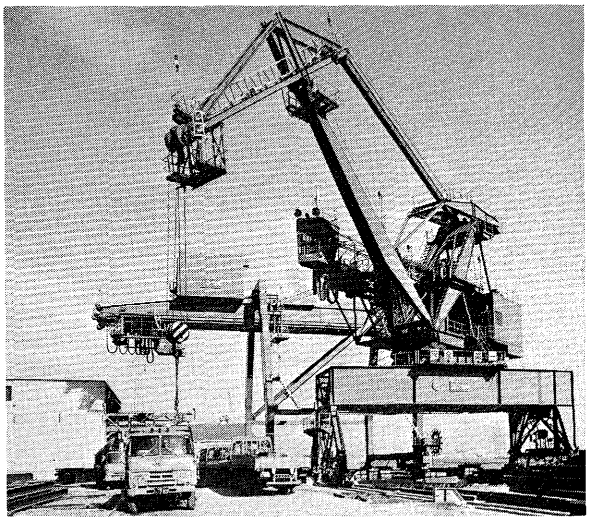


Fig. 2 20 t level luffing crane (US control)

AC unloader and bucket crane sinking, open lowering control, close lowering low speed control, low speed hoisting control of high lift tower cranes and overhead crane replacement. 30 sets of US control system were delivered already.

II. SYNCHRONIZING OPERATION CONTROL

1. Control Explanation

One of the methods for operating several motors at the same speed is the method of providing com-

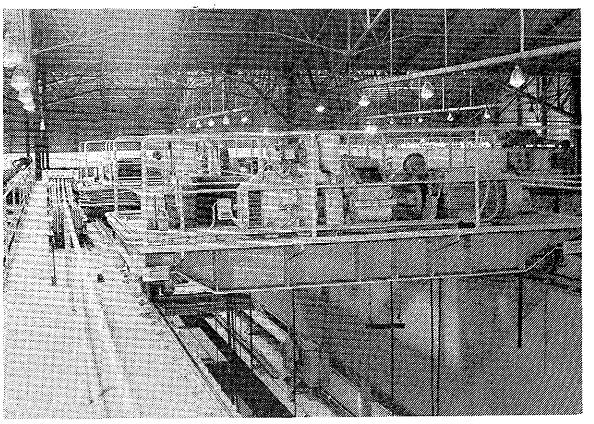


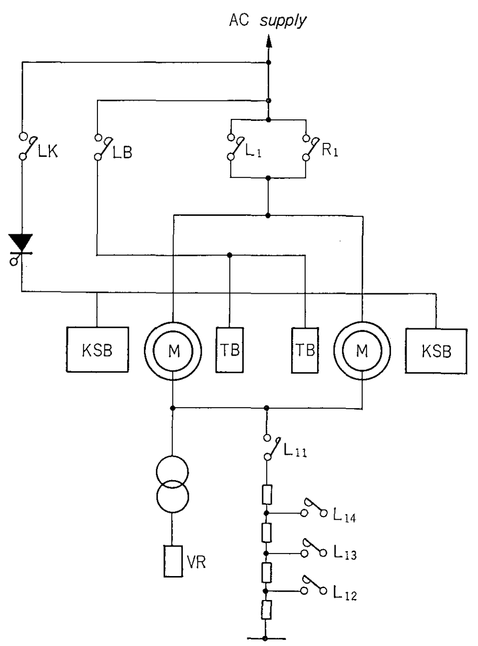
Fig. 3 30 t×47.6 m overhead travelling crane (synchronizing operation for hoisting and travelling)

mon secondary resistance by parallel connection of the rotor circuits of the induction motors. This is known as simple power selsyn.

The conventional system has the following disadvantages: the synchronizing torque during high speed operation becomes extremely low. Even if the speed is reduced by increasing the secondary resistance and the motor speed during light load increases and motor is stepped-out. In addition a brake torque difference occurs in each motor when the motors is stopped by the mechanical brake. Therefore, plural motors can not be stopped in the synchronous state and when restarting, an excessive rush current flows in the motors and electrical and mechnical shocks are given to the crane.

To counteract this, Fuji Electric has developed synchronizing control system employing an eddy current brake (brandname: *KS*-brake). This system is designed to provide enforced stable slip and the certain synchronizing power in motors during light loads. In such a system, hunting of the motor is prevented and at the same time, the same electrical phase angle of each motor is almost maietained. As a result, synchronizing operation with possible schockless restart is can be performed. In other words, the Fuji synchronizing control system is of the electrical shaft type.

The control methods for synchronizing operation are of various types in accordance with the number of separate motors for hoisting, travelling, etc. the degree of load unbadance and the rigidity of the mechanical system. In principle, however, they are all the same in the principle and here an explanation will be given of synchronous operation of two motors for travelling.



M: motor TB: thruster brake
KSB: KS brake VR: voltage relay

Fig. 4 Main circuit diagram of two-motor synchronizing operation for travelling

Fig. 4 shows the connection diagram of the main circuits. The operation in the notches of each of the contactors is as shown in *Fig. 5*. When returning from the operation notch to the zero notch, stopping can be performed while maintaining synchronization as follows.

First, the electromagnetic contactor L_{11} is "opened", the motor drive torque becomes zero and only a secondary circulating current flows for synchronizing. The excitation current of the *KS* brake reaches a maximum and the motor is quickly retarded. The motor is decelerated and once the secondary voltage exceeds a constant value (ex. over 0.95E2) ie. the speed becomes less than 5%, the *LB* is "opened", the thruster brake is applied and the motor is forced to stop. After a fixed period, L_1 or R_1 and *LK* are "opened". When the power source is "open" under such conditions, the motor is not stepped out by an external force from the load side and smooth restarting is achieved.

During light loads, in order that the synchronizing power is not decreased when the speed is in creased, the *KB* brake is excited even at high speed operation, a certain slip is achieved and the synchronizing power is maintained. Since this slip must be 10~20% for traveling or an indoor crane as in the example shown in *Fig. 4*, the selection of the traveling speed is a important factor.

2. Principal of Operation

If the loads of each motor are exactly equal in the circuit connected in common with the secondry resistance of each phase of the rotor side of the wound rotor 3-phase induction motor (refer to *Fig. 6*), both the A and B motors rotate in the same direction with a phase angle difference of zero. The secondary currents flow at an equal rate with the

Contactor	Stop	Coasting notch	#1 notch	#2 notch	#3 notch	#4 notch
L_1 or R_1	×	○	○	○	○	○
L_{11}	×	×	○	○	○	○
L_{12}	×	×	×	○	○	○
L_{13}	×	×	×	×	○	○
L_{14}	×	×	×	×	×	○
LK	×	○	○	○	○	○
LB	×	○	○	○	○	○

Fig. 5 Operational sequence of two-motor synchronizing operation for travelling

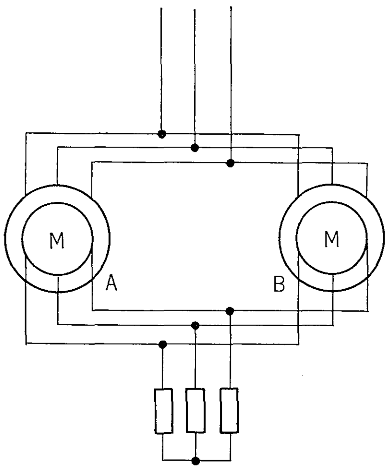


Fig. 6 Main connection of two-motor synchronizing operation

common secondary resistance. If the load of motor B is increased, the rotating speed becomes slower than that of the A motor and the winding of a certain phase of the rotor is cut somewhat quicker than that of the A motor by the revolving field and the phase is advanced. Therefore, a difference arises between the secondary induced voltages of machines A and B a cross current occurs between the two machines. This cross current becomes the motor current in respect to machine B and the generator current in respect to machine A so as make the phase angle difference small. *Fig. 7* shows a simplified equivalent circuit.

If the constants of the A and B motors are equal, the rotation torques of the A and B motors can normally be expressed to the following equations:

$$T_A=\frac{V^2}{(A+B)^2}\left\{A\left(r_1+\frac{r_2+R}{S}-\frac{R}{S}\cos\alpha\right)+B\left(x_1+x_2+\frac{R}{S}\sin\alpha\right)\right\}$$

$$T_B=\frac{V^2}{(A+B^2)}\left\{A\left(r_1+\frac{r_2+R}{S}-\frac{R}{S}\cos\alpha\right)+B\left(x_1+x_2+\frac{R}{S}\sin\alpha\right)\right\}$$

where: $$A=\left(r_1+\frac{r_2+R}{S}\right)^2-(x_1+x_2)^2-\frac{R}{S}$$

$$B=2\left(r_1+\frac{r_2+R}{S}\right)(x_1+x_2)$$

Form this, the synchronizing power between the two motors can be expressed as follows:

$$T_2-T_1=\frac{\frac{2R}{S}B\sin\alpha}{A_2+B_2}V^2$$

As is clear from this explanation, the synchronizing power is at a maximum value at the point

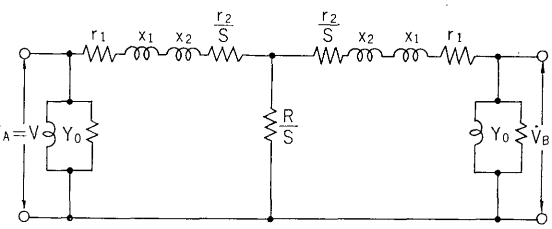
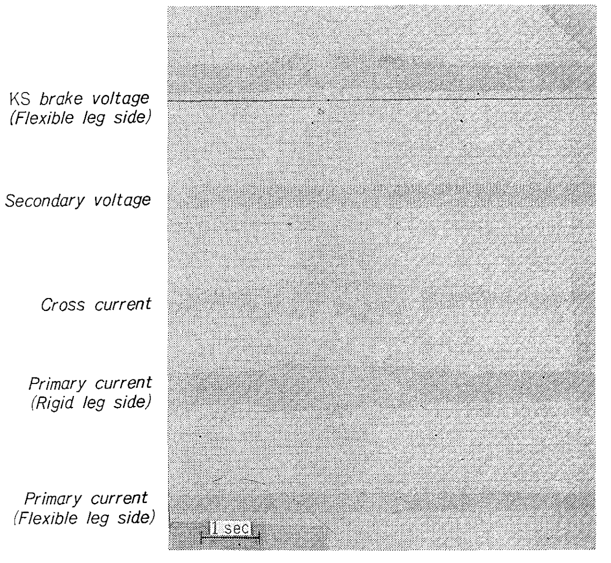


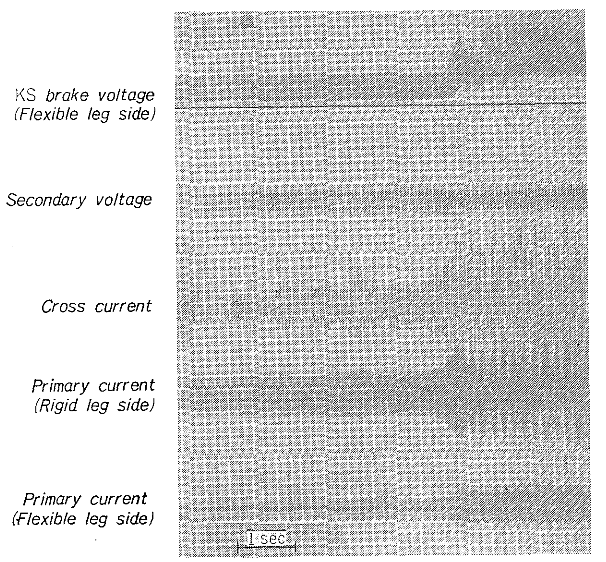
Fig. 7 Equivalent circuit

where the electrical phase angle difference α is 90°.

Since it can be considered that the electrical shaft is the same as the ordinary mechanical shaft in the drive part at both ends, it can be considered that there is electrical torsional vibration. However, when there is sufficient damping in the electrical or mechanical systems to suppress the amplitude of this torsional vibration, the amplitude is dampened even when torsional vibration arises and stability is



(a) Cross current at stable



(b) Cross current at hunting

Fig. 8 Oscillogram of synchronizing operation for travelling of gantry crane achieved. However, when the damping is insufficient, the amplitude becomes diverse and resonance phenomena occur which lead to hunting. When the motor capacities are comparatively small, there are many cases when the internal resistance of the rotor causes a damping effect, but when the capacities are large, the rotor internal resistance and the line resistance become small so that it is necessary to provide a resistor or reactor to insure further damping. (*Fig. 8* (*a*) shows stable operation and (*b*) shows the variations of the primary, secondary and cross currents during hunting.

III. US CONTROL

1. Main Circuit

Fig. 9 shows the main circuit connection diagram of this system. In principle, it is a DC generating brake method in which the braking torque is achieved by DC excitation of the motors. It consists of a simple circuit of a thyristor and diode. In the case of the US control notch, sequential control is achieved with:

75B : ON
52H and 52L : OFF

As a result, the motors are DC excited via the thyrsitor and the braking torque arises. This braking torque arises. This braking torque can be varied by combining the secondary resistance value and the DC exciting current varied by means of a controller. As a result, optional speeds can be obtained.

The speed setting values are applied to the controller to match each lower speed notch and since the actual speed is normally monitored by a tachogenerator, the DC current is controlled so that the set speed is maintained no matter how light the load. Therefore, the $\tau - s$ characteristic curve for this system is as shown in *Fig. 10*.

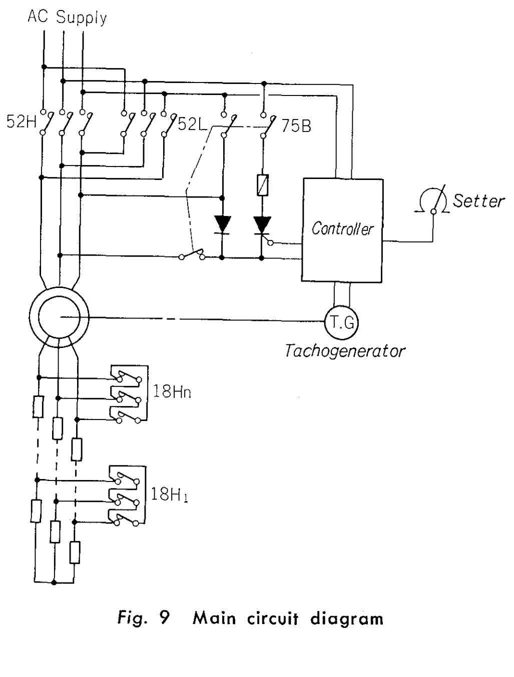


Fig. 9 Main circuit diagram

Fig. 11 shows a block diagram of this control system. In the operation of the control system, the set voltage E_s is applied in accordance with the notch command and is compared with the detected voltage E_T for the actual speed. This compared deviation voltage ΔE is amplified up to a sufficient potential to operate a pulse generator. In this pulse generator, ΔE is converted into a phase control pulse with a phase angle α corresponding to ΔE and this is transferred to the thyristor gate. This thyristor is operated at a certain conduction angle and a DC braking current flows in the motor.

For example, when the set speed value is decreased (when there is a return to the low speed setting notch from the high speed setting notch), the deviation voltage ΔE becomes larger and as a result, the thyristor conduction angle increases, the braking current increases and the braking torque increases so that the speed of the motor is decreased. However, when the speed is decreased to the speed setting value, there is equivalent speed operation at a current value balanced with the load at this point. When the speed setting value is increased (low speed setting notch→high speed setting notch), the result is completely the reverse but there is equivalent speed operation at the new setting command. In other words, the operation occurs at which the set voltage and the detected voltage are almost equal. Since the thyristor conduction angle reaches a maximum when the motor speed settles at the set value, the control current is achieved very quickly and there are few over-run phenomena during low speed switching those which occur in conventional dynamic brake control.

2. Current Sharing

The crane motor can be considered as the resultant load of a resistance R with no counter emf.

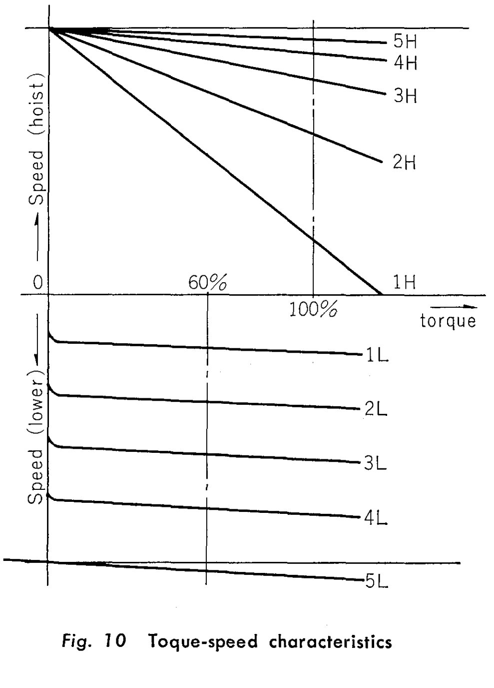


Fig. 10 Toque-speed characteristics

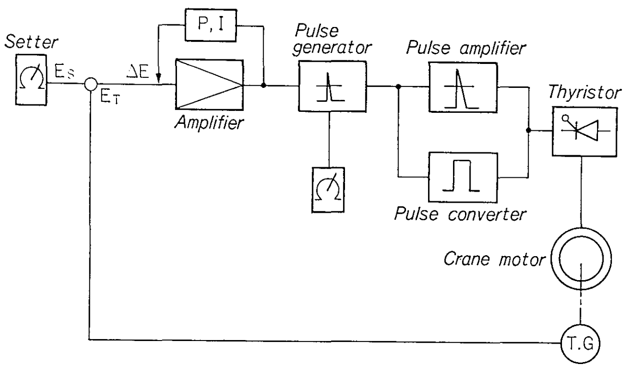


Fig. 11 **Control system block diagram**

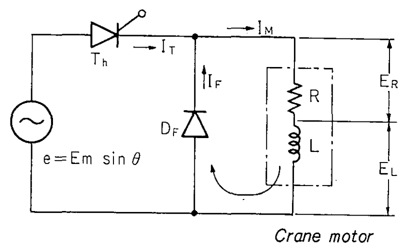


Fig. 12 (a) **Equivalent circuit**

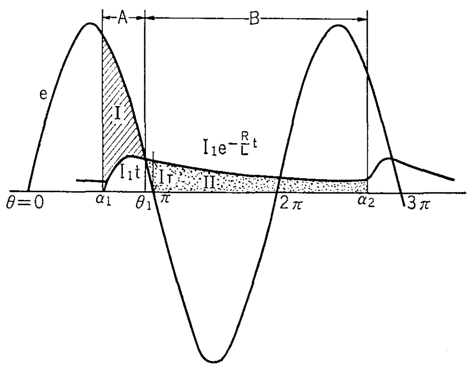


Fig. 12 (b) **Current waveform**

and an inductance L. It is a DC halfwave rectifying circuit with a free wheeling diode attached. *Fig. 12* shows the equivalent circuit diagram of the main circuits and the current waveforms. When fired at the phase angle α_1, the power supply voltage at $\theta=\alpha_1$ is applied to the load but since the inductance L shares the total voltage, the current I_T does not flow. However, in the course of time, the current I_T increases but the difference between the power source and the resistant component voltage drop E_R is shared by L as absorption energy and is accumulated up to the angle θ_1 when the power source and E_R become equal. Then, when θ_1 is exceeded, the load cprrent I_M flows consisting of the power source supply component and the discharge current component of L. However, when $\theta=\pi$ is exceeded and the power source voltage becomes negative, the thyristor (*Th*) is turned off and disconnected from the power supply circuit. On the other hand, the free wheeling diode (D_F) is further forward biased at that moment and a current through D_F as the short circuit current (I_F) by means of $-E_L$. This continues to flow until the absorbed energy is released and I_T is decreased by the $e^{\frac{-R}{L}T}$ function of LR. This indicates that the area component of absorption energy I is equal to the area component of discharge energy II.

Since the L component of the crane motor is relatively high in the US control, $I_F>0$ even at the next firing point α_2 and current flows continuously. The braking current I_M is made up of the period A of thyristor current I_T which is supplied from the power source and the period B of the diode current I_F which flows due to the discharge of L. This sharing differs in accordance with the phase angle α and the motor capacities but generally I_L is $\frac{1}{3}\sim\frac{1}{4}$ of I_M. In other words, the main thyristors current can be considered to be about 30% of the total braking current.

3. Torque Characteristics

As was described previously, the DC braking current is controlled by single phase half wave control using a free wheeling diode so that it is a direct current including an AC component. *Fig. 13* shows the details of the current waveforms. This AC component is considered to act as a damping com-

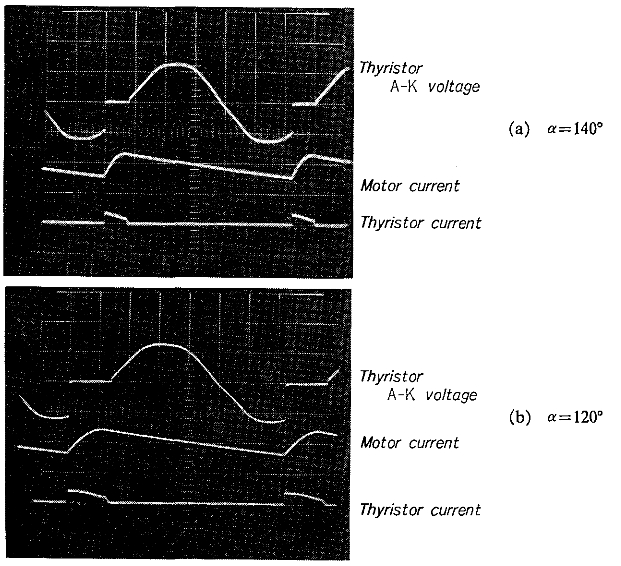


Fig. 13 **Current waveform**

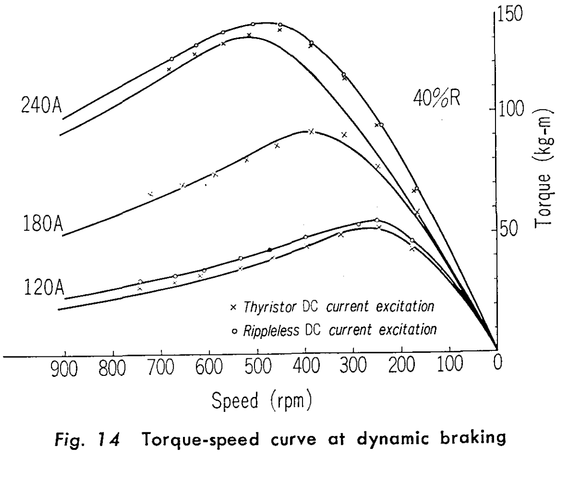


Fig. 14 **Torque-speed curve at dynamic braking**

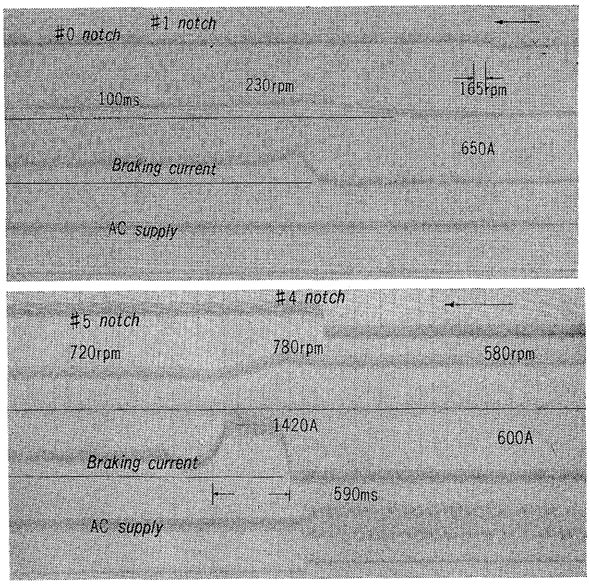


Fig. 15 Oscillogram of 150/35 t×19.5 m ladle crane main hoisting (motor: 2×160 kW) US control

ponent to decrease the braking torque, but from the results of actual measurements, it can be considered that it has the same characteristics as the speed torque characteristics due to pure DC excitation. *Fig. 14* shows the actually measured values of the speed torque characteristics by means of US control and the design values of pure DC excitation.

4. Transient Characteristics

The US control system has a DC braking current flowing in accordance with the lowering weight. Therefore, at the time of light loads, there is only a small braking current flowing so that the internal motor loss can be less than that of conventional DC generating control. At the time of notching from the high speed lowering notch to the low speed notch, there is automatic excess excitation and the retarding effect can be speeded-up.

IV. APPLICATIONS

1. Synchronized Operation of Several Crac Cranes

When long span steel plates are transported in steel works and shipyards, several crab cranes with a lifting magnet attached are often used (*Fig. 16*). Since the size of the long span materials is normally not constant, the crane can be positioned to match the long span material by independent operation of each crab crane. Then the lifting magnets are lowered to pick up the material. These lifting magnets are strong for perdendicular loads but weak for horizontal loads so that it is necessary to operate two lifting magnets at exactly the same lifting speed. When the lifting speeds are unequal, horizontal force components arise which might cause the load being hoisted to be dropped. The Fuji Electric synchro-

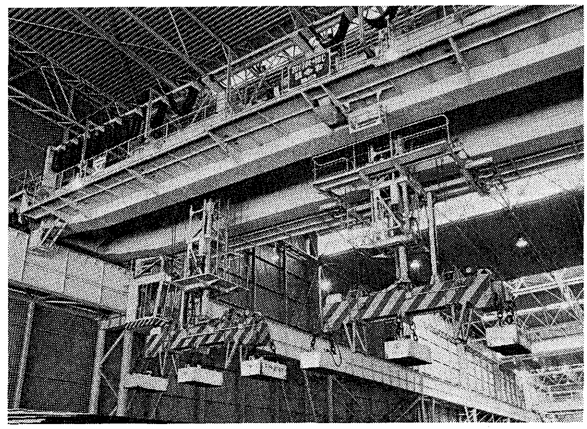


Fig. 16 (10+10) t×29 m overhead travelling crane/ synchronizing operation for hoisting

nizing operation control system is highly effective in such cases. *Fig. 12* shows a skeleton diagram of this system. Secondary resistors and contactors are connected to each motor to permit independent operation. The electromagnetic contactor HD is excited during simultaneous operation and a cross current circuit is achieved. During lifting, the secondary resistors are short circuited in accordance with the notch but during lowering, speed control is performed with all resistors connected until the final notch and the motor power consumption is suppressed.

The KS brake in this system not only maintains a constant amount of slip for both lifting and lowering but also makes possible low speed operation control and effectively absorbs the control energy during stopping.

Fig. 18 shows the KS brake exciting current and the electromagnetic brake timing during stopping from the lowering high speed notch. When the notch

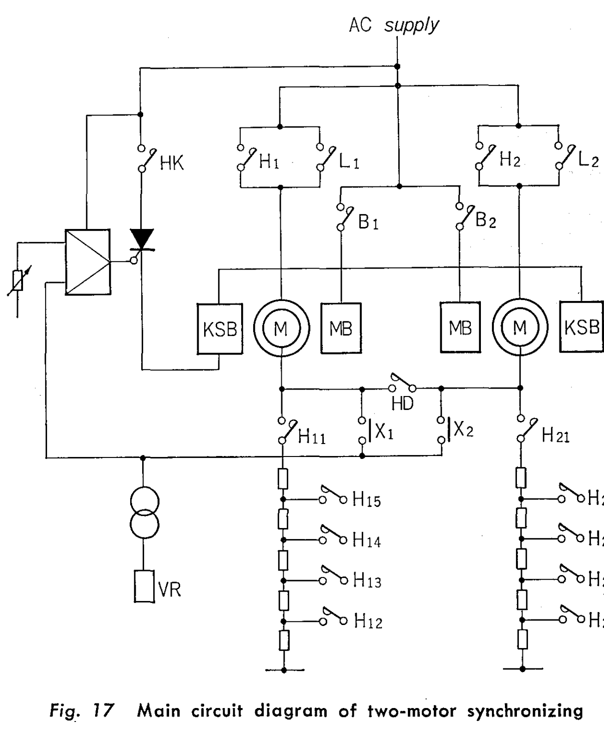


Fig. 17 Main circuit diagram of two-motor synchronizing operation for hoisting

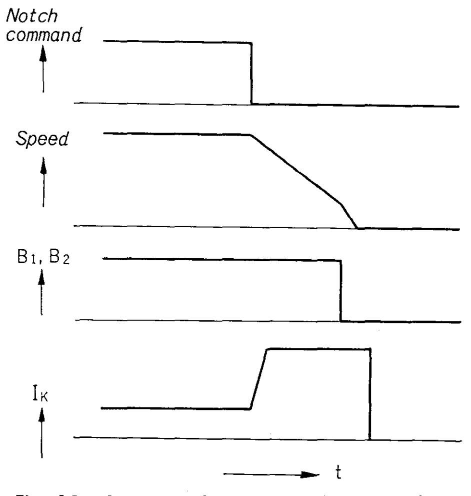


Fig. 18 Operational sequence of circuit relay

command is returned from the final lowering notch to the 0 notch (stop notch), the automatically controlled KS brake exciting current is increased to its maximum value and a large deceleration effect is produced. Since the electromagnetic brake is not operated unless the secondary voltage value is more than the constant value (the speed is lower than the constant value), the major part of the control energy is born by the KS brake. Generally, the KS brake excitation control equipment has a margin of as much as 2—3 times the ratings and a sufficiently high response rate can be obtained with only the KS brake. Even if the high frequency service for this system in steel works, where the operating frequency is very high, the electromagnetic brake lining has been found to have a life of more than two years.

2. Simultaneous Hoist Operation With Crab Cranes of Different Capacities

When the degree of unbalance of the loads applied to the crab cranes is particularly high (it is necessary for the synchronizing power to be especially high), the control system as shown in *Fig. 19.* can be considered. The KS brake, electromagnetic brake, etc. are not included in *Fig. 19.*

This example has been used in the control of cranes of different capacities and equivalent speeds. One motor of the No. 1 crane and the motor of the No. 2 crane are connected in the power selsyn system with the secondary resistance released. The lowering acceleration power source is from the A motor of the No. 1 crane.

3. US Control System for Bucket Cranes and AC Cranes

Generally, the control of two-motor equal capacity bucket cranes and unloader are problems of sinking control and open lowering control. Sinking is the case when the closing motor is operated in the closing direction at the same time as the holding motor is operated in the downward direction when the load is grasped. When grasping is by means of

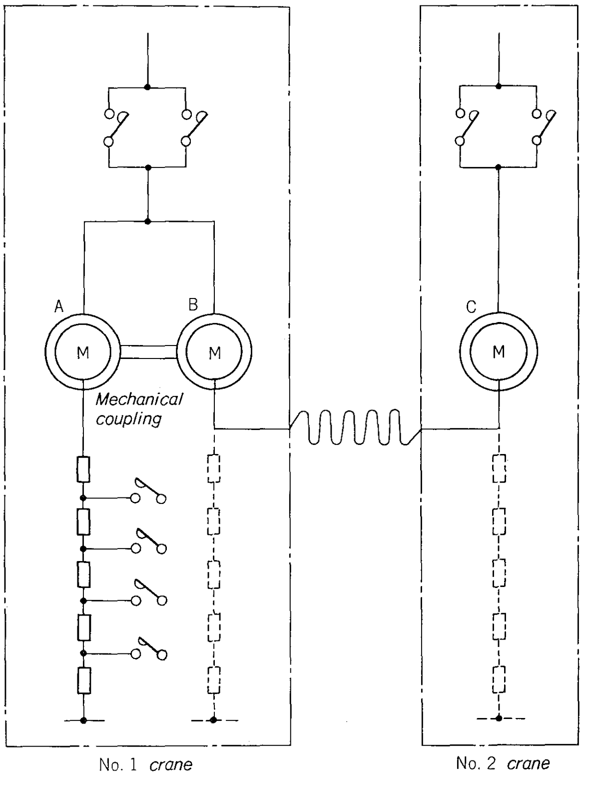


Fig. 19 Example of main connection of two-crane synchronizing operation for lowering

Fig. 20 120/60 t×47.2 m overhead travelling crane (synchronizing operating, traversing and travelline)

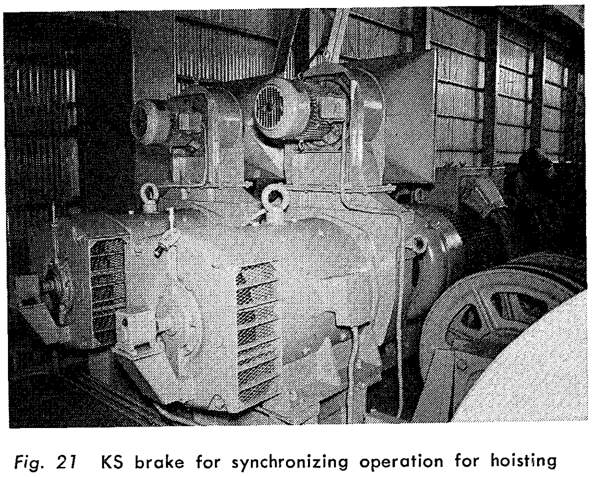


Fig. 21 KS brake for synchronizing operation for hoisting

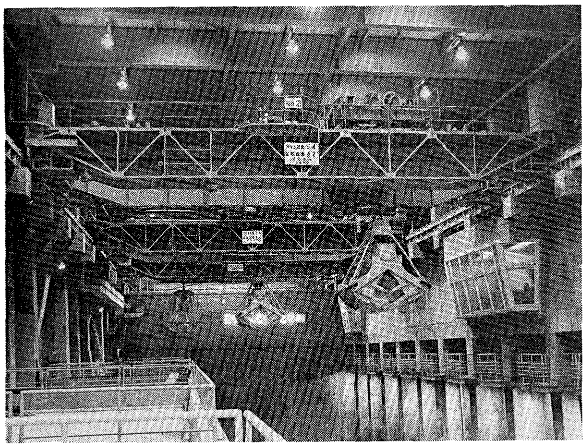


Fig. 22 9.4 t overhead travelling crane with bucket

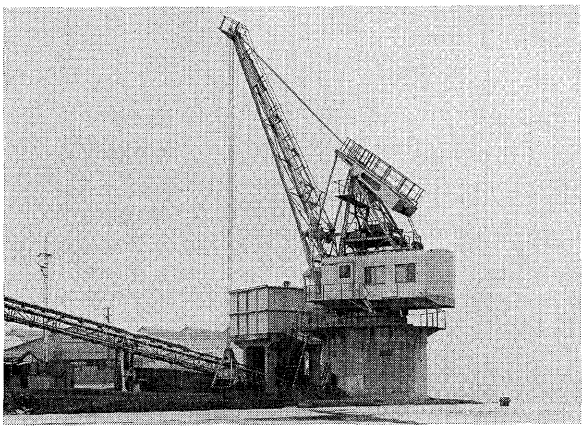


Fig. 23 7 t jib crane with/bucket

only the closing motor, sufficient grasping of the load is impossible because of the bucket structure. In other words, it is necessary to lower all of the buckets during grasping operation.

During lowering with the buckets opened, the total weight of the buckets is applied to the holding rope so that the speed of the holding motor is greater than that of the closing motor and the closing rope is stretched. Therefore, some tension is applied to the closing rope and this causes bucket's closing. When the lift is large, the buckets are often completely closed. This results in a very bad load efficiency. For the crane to operate at good efficiency, there must be control so that the bucket is not closed during lowering.

The Fuji US control system solves this problem economically. The sinking control performs closing operating during grasping by rotating the closing motor in the closing direction and the holding motor is switched over to US control. *Fig. 24* shows this principle. For example, when the speed is set at 20%, the buckets begin to sink by their own weight because of the sinking command. At this time, the sinking speed of the buckets is less than the set value, the thyristor conduction angle is 0°, there is no DC braking current and the buckets sink rapidly by their own weight. As soon as the sinking speed exceeds the set value, braking is applied, and the sinking

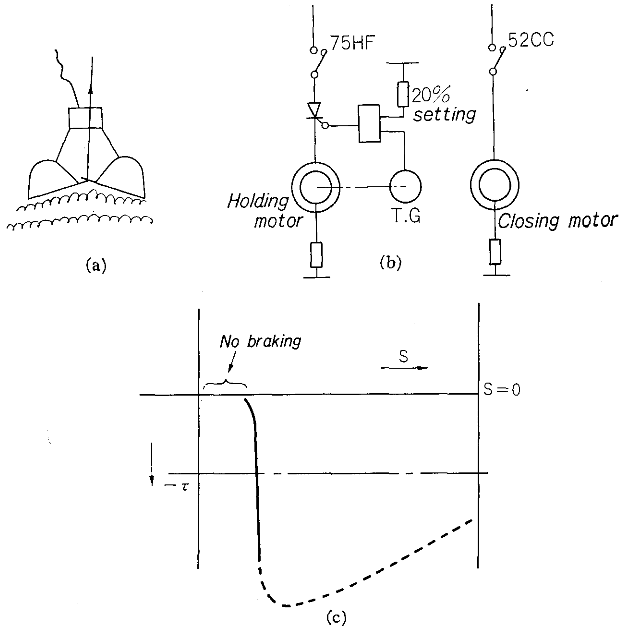


Fig. 24 Diagram of "sinking"

speed is limited. Therefore, effective sinking can be obtained with no separation of the rope from the drum grooves due to abnormally rapid sinking speeds.

It is important that no tension should occur on closing rope in open lowering control period. The closing motor normally only draws out the rope and if it is so controlled that the entire weight of the bucket is born by the holding rope, there is no variation in bucket closing. The US control during open lowering applies this principle and this is explained in *Fig. 25*. In this case, control is such that the holding motor speed follows that of the closing motor. The holding motor thyristor control equipment automatically coutrols closing speed generator output at so the setting speed that the holding rope bears the total bucket weight, the closing motor simply draws out the rope and lowering is possible without bucket closing. *Fig. 26* shows the actual speed changes.

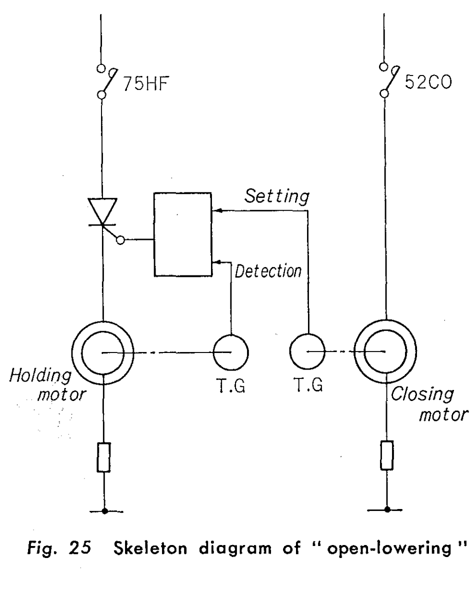


Fig. 25 Skeleton diagram of "open-lowering"

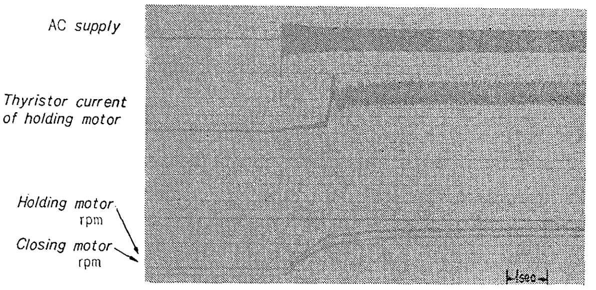


Fig. 26 Speed change of open-lowering "

4. Efficient Crane Design by US Control System

By utilizing existing over head crane girders, it is often required to increase the efficiency of the cranes by increasing the hoisting speed. Since the motor capacities are increased in such cases, the brake capacity for control must also be larger, but the sufficient space can not be expected on the crab girder.

In the example shown in *Fig. 27,* the length of the motor drive shaft increases comparing with the drum shaft. This can also be said concerning a low lift over head crane and when making a design to match the drive shaft side, the crab becomes larger and the approach performance of the crane deteriorates.

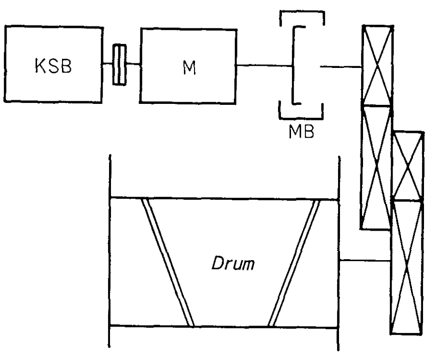


Fig. 27 Construction of hoisting machine

The drive shaft in US control only has the tachogenerator so that special control brakes for the motor are not required and the machine design is more efficient.

5. US Control of Jib Cranes

In the case of high lift jib cranes and overhead cranes control is performed so that lifting is at high speeds during light load hoisting by pole changing wound rotor motors. In the case of cranes used for assembly of large structural parts, low speed hoisting is required. The US system is also highly effective in such cases.

Fig. 28 shows the main circuit connection diagram. As an example, the drive motors are 12P and 6P pole changing motors. When low hoist speeds are required at high speed operation (6P), the rotating force due to the AC current in the rotor and the control force due to DC fixed excitation are superimposed if a DC exciting current flows in the 6P winding and the DC braking current controlled by the US system flows in the 12P winding. Since stator winding is switched over from delta to star connection by external contactor at the AC drive side, over excitation of the motor rotor can be prevented.

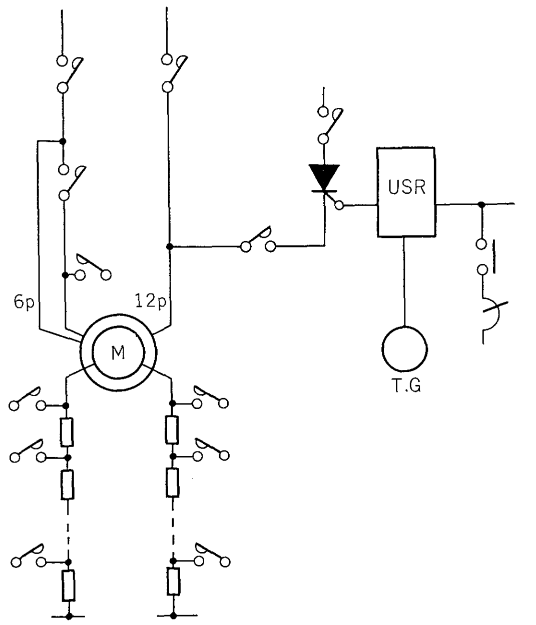


Fig. 28 Speed control of pole-change machine

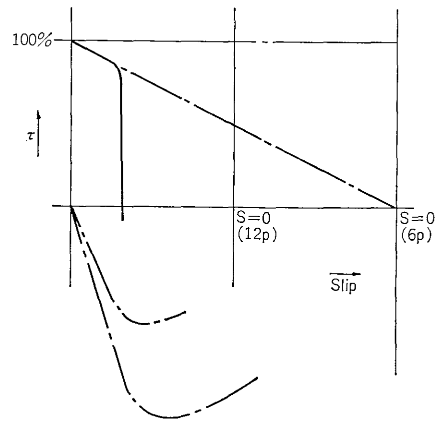


Fig. 29 Torque-speed characteristics

Since the control torque peak is in the low speed range due to DC control when speed control is performed at low speeds, the secondary resistance value must be small but the increase in the drive torque caused by the AC component can be suppressed by star connection and effective low speed control is achieved. *Fig 29* shows the τ-s characteristic curves.

V. CONCLUSION

Fuji Electric has performed research on the optimum control systems for various objectives in highly diversified crane applications. Synchronizing operation of wound rotor three-phase induction motors by means of common secondary resistance has been employed in machine tools and has also been partially used for travelling of small capacity gantry cranes and overhead cranes. However, because of the wear and shock of the contacts caused by starting rush currents in cranes where starting and stopping are repeated frequently, these systems have not become practical. The Fuji synchronizing operation control also uses an eddy current brake which solves this problem and makes the system practical. This system does not perform feedback control by detecting differences in speeds and lift but performs complete open loop synchronizing by means of an electrical shaft. Therefore, the control and equipment construction are simplified and of high reliability.

The US control, on the other hand, can be called a modification of the DC generating brake control. Its main advantage is that it makes possible low speed lowering control with light loads. The speed control equipment is more lightweight and compact and less expensive than the conventional eddy current brake control system and the thruster control system. Crane lowering control will probably be performed in the future mainly by thyristors in such control equipment.