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"MECHANICAL AND ELECTRICAL REDUNDANCY CONSIDERATIONS FOR MOVABLE BRIDGE SYSTEMS"

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Mechanical and Electrical Redundancy Considerations

for

Movable Bridge Systems

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Introduction

Several different control options are available today for movable bridges. The type of control chosen and it's implementation are determined to a large degree by the mechanical and structural features of the bridge, and to what extent the mechanical drive redundancy is to be exploited.

Redundancy, both mechanical and electrical, is a desirable feature in any movable bridge system, because it allows the bridge to remain in operation with one or more component systems out of service. The majority of movable bridge control applications today involve existing structures where the mechanical system is in place, and the degree of mechanical redundancy is already established. It then becomes the task of the control designer to exploit the existing mechanical redundancy when designing the electrical control system, and to incorporate electrical redundancy where practical to improve overall system reliability.

Movable Bridge Mechanical Systems

New control requirements can best be determined by looking at a few of the more common mechanical drive systems by bridge type, such as Swing, Bascule, and Vertical Lift, and by examining earlier electrical control systems used on these bridges.

Figures 1 and 2 show two of the more common Swing Bridge motor and gearing arrangements. In both configurations, multiple motors and pinion gears drive a single main gear to rotate the bridge structure. Multiple pinion gears are used to eliminate lateral main gear bearing forces, and to minimize pinion and main gear tooth loading.

While multiple motors are used in each arrangement, the gearing system delivering motor torque to the pinion gears differs, and determines the degree of mechanical redundancy. The gearing arrangement of Figure 1 is simple with independent reduction for each motor / pinion pair. The gearing arrangement of Figure 2 is more complex and incorporates intermediate gearing ahead of the final pinion reduction. Redundancy is provided in each case because a single motor providing a higher torque can be used to move the structure. However, the arrangement in Figure 2 will provide balanced pinion gear torques with no lateral main gear bearing loading.

In normal service, each motor in both cases will operate at the same speed due to the mechanical nature of the system, and as such, speed matching is considered noncritical. Torque or load sharing is somewhat more important for the arrangement of Figure 1 than that of Figure 2, because, unbalanced driving torques from the arrangement shown in Figure 1 will lead to lateral main gear bearing loading.

Figures 3, 4 and 5 represent three common Bascule Bridge motor and gearing arrangements. The common shaft system shown in Figure 3 utilizes multiple motors in a common location driving intermediate gearing. A common shaft transmits balanced torques to the final trunnion gear reduction located on each side of the span. This system can employ two motors of the same horsepower, or a main / auxiliary motor arrangement where the axillary motor is smaller and operates the structure at a slower rate.

The intermediate shaft system shown in Figure 4 uses two motors of the same size, one for each side of the span. Each motor drives a final trunnion gear reduction located with the motor. An intermediate speed shaft is used to connect the two final gear reducers and to transmit differential or balancing torques from one side of the span to the other.

Again, redundancy is provided because a single motor can be used to move the structure. Both the common shaft arrangement of Figure 3, and the intermediate shaft arrangement of Figure 4 will operate with a single motor and without transmitting twisting torques and forces through the main span structure.

The system shown in Figure 5 is termed the Chicago Style arrangement. As in Figure 4, two motors of the same size are used to drive the final trunnion gear reduction located with the motor on each side of the span. However, there is no intermediate shaft connecting both sides. There is no redundancy here as a single motor can not operate the span without requiring the structure to transmit forces from one side to the other. As mentioned previously, this action results in the production of a twisting moment in the span structure.

In normal service, the multiple motors of the systems shown in Figures 3 and 4 will operate at the same speed due to the mechanical nature of the system, and again speed matching is considered noncritical. However, the Chicago Style system shown in Figure 5 requires precise speed and load matching of the two motors so that twisting moments are not generated in the span structure. Speed and load matching for the Chicago Style arrangement shown in Figure 5 are considered critical.

Finally, the Span Drive and the Tower Drive for vertical lift bridges are shown in Figures 6 and 7. The Span Drive of Figure 6 shows two motors of the same size in a common location on the span and driving intermediate gearing. A common shaft transmits balanced torques for the final cable drum reduction. Both motors operate at the same speed due to the mechanical nature of the system, and redundancy is provided because a single motor can be used to move the structure. Speed matching is considered noncritical for the Span Drive shown in Figure 6.

The Tower Drive shown in Figure 7 uses four motors of the same size, two motors per side in each tower. Each end or tower lifts independently. The motors of each tower operate at the same speed due to the mechanical nature of the local system, however, end to end or tower to tower speed matching is considered critical to prevent span skew and jamming. Redundancy is provided within each tower motor pair but not unnecessarily tower to tower. An additional wound rotor motor is often employed in each tower, and electrically connected to it's counter part in the other tower. This connection is termed a Power Synchro-tie and is used to transmit differential or balancing torques electrically from one tower system to the other. The primary purpose for this system is to insure tower to tower or end to end position matching to eliminate skew and jamming, but, the presence of these motors also increases redundancy. For example, should a tower motor become inoperable, the Synchro-tie connection will distribute required makeup torque from one tower system to the other. The electrical action of this system will be covered later.

Traditional Control Configurations

Traditional control configurations can now be reviewed for features, operation, and redundancy. The earliest control system in use was the Drum controller as shown in Figure 8. This controller was primarily used with AC Wound Rotor Motors and could provide duplex or multiple motor control. Operation was manual and provided stepped, plain reversing motor control by inserting or removing motor secondary resistance. Slowdown of a moving structure was provided manually by the operator using counter-torque braking.

These controllers were used to operate bridge systems with noncritical speed matching requirements. When multiple motors were controlled, the torque or load balance between motors was accomplished by trimming each motor's resistors.

As can be seen, there is no electrical redundancy with only a single controller. Often, lack of electrical redundancy for Drum control was not considered critical due to the simplicity of the control system, and the relative ease of troubleshooting and repair.

The stepped contactor control shown in Figure 9 controlled motors in a similar manner to that of the drum controller with the added feature of electrical command operation. This system provided the means to operate multiple controllers simultaneously from a remote location. Stepped contactor systems also provided automatic acceleration and counter-torque control. As with Drum controllers, these controllers were used to operate bridge systems with noncritical speed matching requirements. And again, when multiple motors were controlled, the torque or load balance between motors was accomplished by trimming each motor's resistors.

A two motor duplex controller could operate a single motor in noncritical speed and load match systems with the second motor out of service, and as such, exploited the system mechanical redundancy. However, the single stepped contactor controller of Figure 9 did not provide any electrical redundancy. With this system, electrical redundancy could be supplied only by means of an auxiliary system, either another electrical control or some other means such as a diesel mechanical or hydraulic system.

The adjustable voltage DC system shown in Figure 10 (sometimes referred to as a Ward-Leonard system) controlled multiple shunt wound DC motors, and was used to operate bridges with critical speed and load matching requirements such as the tower drives of vertical lift bridges. This system provided very accurate and smooth stepless control, true power regeneration capabilities, and very good speed matching due to the flat load regulation characteristics of the shunt wound DC motor. Multiple DC generators and amplidynes were sometimes used to provide tower to tower position control to minimize span jamming.

The power components of this system consisted of rotating equipment, and as such were considered very reliable with periodic inspection and maintenance. But the fact remains, that a single controller does not provide electrical redundancy, and axillary or secondary systems must be in place for this purpose.

The wound rotor motor Synchro-Tie system shown in Figure 11 was also used for tower drive control of vertical lift bridges. This system typically consisted of two controllers, one in each tower, controlling one or more wound rotor motors. The distinguishing feature of this control was the Synchro-tie motor in each tower. These motors were mechanically tied to the main driving motor or motors in each tower and electrically tied to each other, tower to tower.

In operation, the Synchro-tie connection provided a tower to tower electrical path for differential torque or loading. Figures 12 and 13 show the compensating torque levels and currents as a function of motor to motor rotor displacement angle at stall. As can be seen, with as little as 20 degrees of displacement, full load torque could be developed. Figures 14 and 15 show that the developed torque remained essentially constant when the Synchro-tie motors are operated at slip values greater than 1. This system thus provided a means of precise position matching between towers with only a slight mechanical phase difference at constant speed.

The Synchro-tie system was essentially the first control scheme to provide mechanical and electrical redundancy. If a main motor was taken out of service, the required makeup torque would be provided by the Synchro-tie connection, and power would be transferred electrically as needed from tower to tower. If the Synchro-tie motors were large enough, sufficient torque could be transferred by the electrical connection alone to provide the total tower torque requirements with one tower's electrical control out of service. This is true electrical redundancy.

AC Static Control Configurations

Today, bridge renovation projects often include the replacement of aging traditional controls with higher performance static systems. Again, by analyzing the bridge's mechanical requirements and existing redundancy, the configuration of these systems can often be simplified. A simple, minimum system is easy to setup and maintain, and will provide reliable service.

Renovation project specifications will require one controller per motor in order to provide electrical system redundancy. Referring back to the mechanical systems discussed earlier, the one control per motor requirement will provide electrical redundancy for noncritical speed match systems only. And this is true only when the control is capable of operating the remaining motor or motors under the resulting increased loading at higher current levels.

A static thyristor control configuration that is frequently used is the Master / Slave arrangement shown in Figure 16. This configuration can be applied to critical and noncritical speed matched systems alike. In operation, there are two control systems, each acting independently to control it's connected motor in relation to a common speed reference ramp signal. A common reference signal is used because precisely matching two independent ramp signals is a virtually impossible task. The common signal is generated from the control system designated to be the Master system. Using a common speed reference ramp signal simplifies the overall control setup by eliminating the requirement to precisely match ramp rates and individual speed end points. Since these systems operate as closed loop controls from a common speed reference signal, load sharing and speed matching is accomplished by adjusting the slave or master feedback signal while monitoring motor currents.

In noncritical speed matching systems, mechanical redundancy will be maintained because either motor can be removed from service while the remaining motor and control will assume the total load burden assuming that the control and motor are sized appropriately for this temporary service condition. Electrical redundancy is also maintained if provision is made for the slave control to generate it's own speed reference ramp signal in the absence of the master control ramp signal.

The Master / Slave arrangement just described can be applied to most movable bridge systems including the Tower Drives of vertical lift bridges. This control arrangement performs well in this application by maintaining good tower to tower span position. Mechanical redundancy within a tower system is provided as just described, and can be provided tower to tower if Synchro-tie motors are in place. Electrical redundancy can also be provided with the appropriate control provisions discussed previously.

The Master / Slave arrangement is also preferred for the control of critical speed matched systems, such as the Chicago Style bascule bridge. By virtue of independently controlling each motor to a common speed reference signal, each system can compensate for variations in motor to motor loading and eliminate each motor's load regulation characteristic. Neither mechanical nor electrical redundancy exists in this application.

A variation of the Master / Slave arrangement is sometimes used in noncritical speed matched applications where not only is the speed reference ramp signal generated by the master control, but total system speed regulation is provided also. Only phasing or gating signals are sent to the slave thyristor control. This arrangement requires that motor to motor load balancing be accomplished by trimming motor secondary resistance similar to the practice used in stepped controls. This arrangement provides mechanical redundancy under the same requirements of the previously described Master / Slave system, but can provide electrical redundancy only if a local speed reference ramp signal and a speed regulator circuit with feedback can be provided for the slave system. This Master / Slave arrangement is not recommended for the control of critical speed matched systems such as the Chicago Style bascule bridge.

Another arrangement sometimes used with multiple motors and controls is the Tach Follower system shown in Figure 17. This system is comprised of a Lead system and a Follower system. The Lead system establishes the performance in terms of speed and acceleration rate while the Follower system "follows" by using the Lead system speed feedback signal as a speed reference. This arrangement can be applied only on noncritical speed matched systems due to follower delay or response. In the Master / Slave arrangement just presented, the individual control responses occur concurrently, such that the speed corrections for each motor happen together and at the same time thus providing close control over speed and load sharing. In the Tach Follower system, the individual control responses occur in series and are additive since the Follower system must wait for the Lead system. This action prevents precise speed and load matching because the Follower system is always behind. This arrangement can be applied to systems such as multiple leaf bascule bridges where it is desirable to have the leaves raise and close together, but absolute speed and load matching are not required. As with the Master / Slave arrangement presented earlier, mechanical redundancy can be maintained, and electrical redundancy can be provided if provision is made for a local speed reference ramp signal for the Follower system.

The final arrangement to be presented is the Alternating Duplex Control shown in Figure 18. This configuration can be used on noncritical speed matched systems, and consists of two complete controls, each one capable of driving all motors in the system. Each panel is used singly to control the motors with an alternating function to share the run time of each system. The alternating function is also responsible for the motor power transfer circuit which connects the motors to the active control panel. Load sharing between motors is adjusted by trimming the motor resistors as with stepped systems.

This system is easy to setup as no signals are required to be shared between the controls. This system provides mechanical redundancy in the same manner as the previous Master / Slave arrangement with the added assurance that the control panel can supply the required additional load current due to the duplex design of the control. Electrical redundancy can be provided automatically with this system. Should the commanded motion not be achieved within a specified time, the control system can be designed to automatically transfer control to the alternate system and remain locked in a non alternating operating sequence until corrective maintenance can be performed.

Summary

Figure 19 summarizes the differing movable bridge systems and their characteristics, and shows that most movable bridge arrangements can be considered as noncritical speed matched systems where the motors operate at the same speed due to direct mechanical coupling. Load sharing in these applications is accomplished by trimming the motor resistors or through control system adjustments when possible. Load sharing is important even in noncritical speed matched systems to maintain even motor loads and torques and to minimize unbalanced mechanical loads to prolong structure and gearing life. Noncritical speed matched systems possess mechanical redundancy through the direct mechanical connection of the driving motors. If one motor is taken out of service, the remaining motor or motors can temporarily provide the additional required torque.

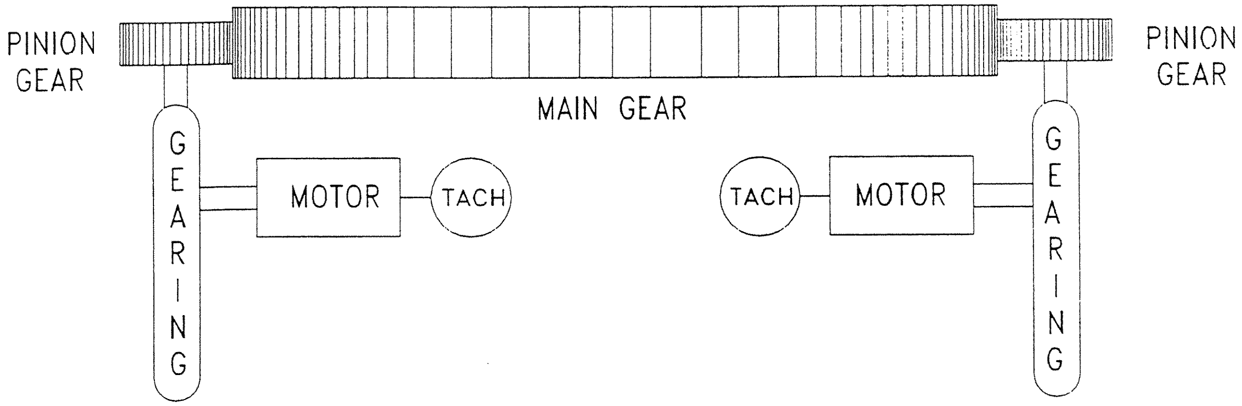
Critical speed matched systems such as the Chicago Style bascule bridge require very accurate speed and load matching to prevent twisting loads from being developed in the span structure. This bridge arrangement does not posses mechanical redundancy, and the static systems employed for control do not inherently provide electrical redundancy. Auxiliary drive and control systems are necessary to satisfy these requirements.

The Tower Drive vertical lift bridge is considered a critical speed matched system when the tower to tower position requirement is considered. If Synchro-tie motors are present in an existing system, mechanical and electrical redundancy can be maintained with new control designs through the continued use of the Synchro-tie motors.

New static controls installed during renovation projects can improve bridge system reliability by utilizing existing mechanical redundancy and by offering simple electrical redundancy. Master / Slave static controls can be applied to most bridge systems, but Alternating Duplex controls bring simple operation and automatic electrical redundancy to many applications.

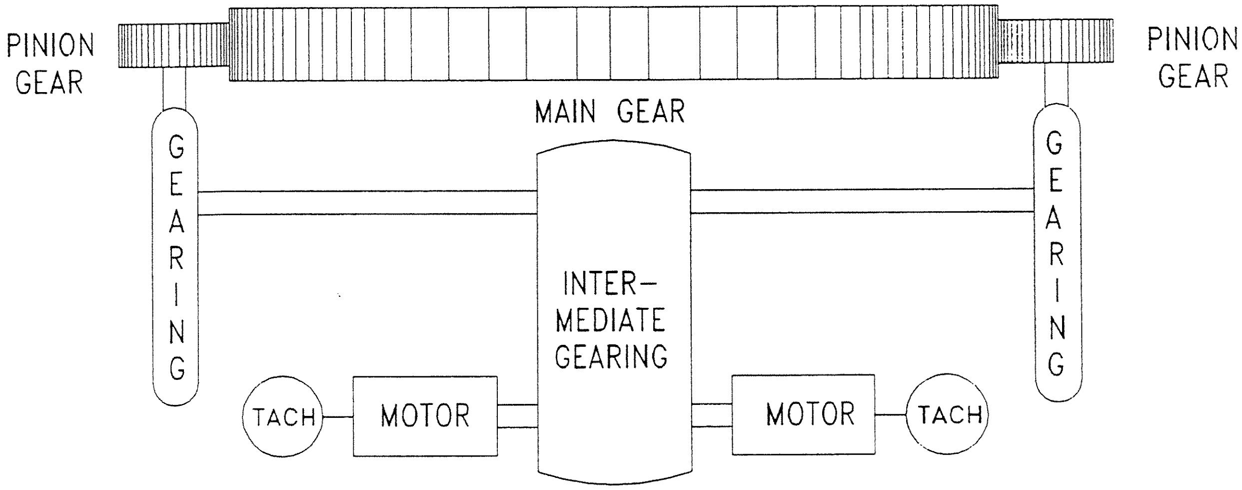
And finally, electrical redundancy, when possible, can be provided by the control system only if the control components comprising that system can operate at the higher temporary motor currents required of the remaining motors. This is an important factor and must be considered in the final control design.

SWING BRIDGE MOTOR AND GEARING SCHEMATIC



SWING BRIDGE DRIVE

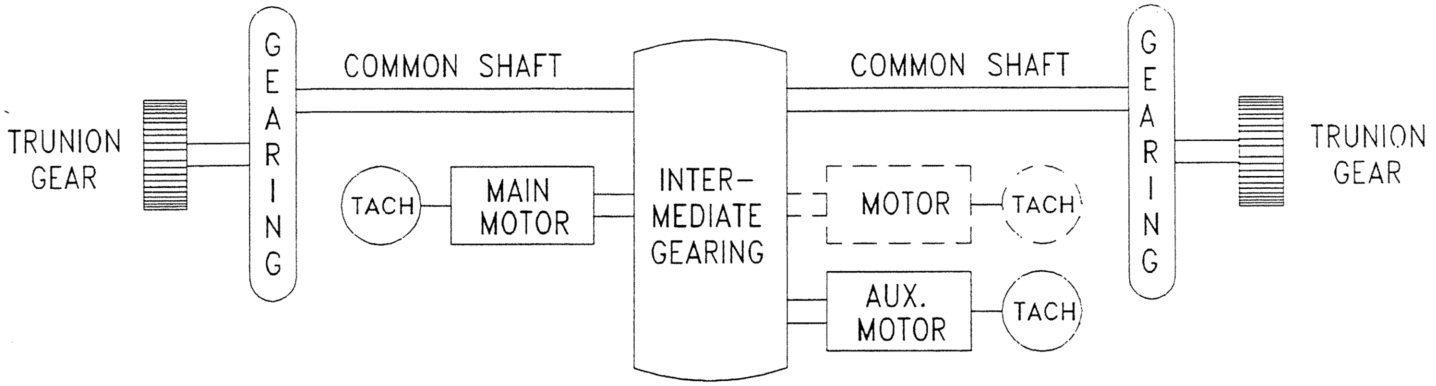
2 OR MORE MOTORS/SPAN
INDEPENDENT GEAR REDUCTION
(ONE PER MOTOR/PINION)
FIG 1



SWING BRIDGE DRIVE

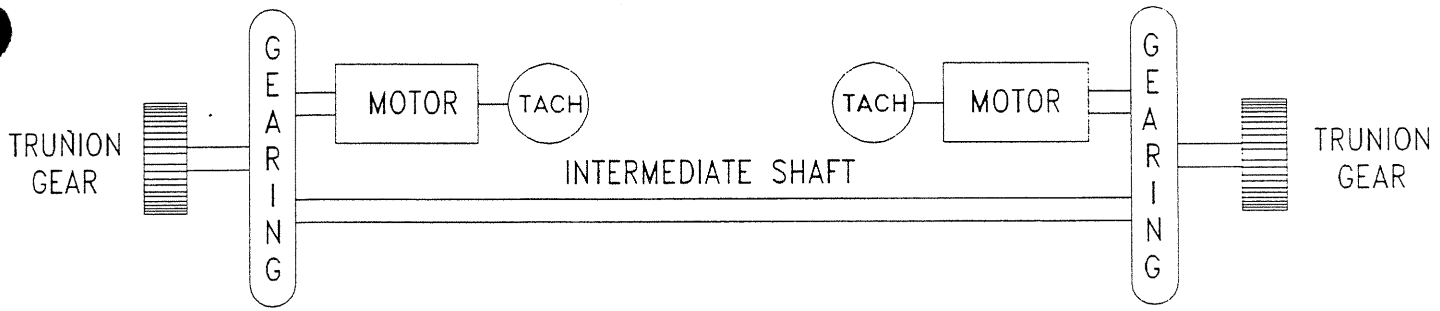
DUAL MOTORS/SPAN
INTERMEDIATE GEARING
WITH DUAL FINAL REDUCTION
FIG 2

BASCULE BRIDGE MOTOR AND GEARING SCHEMATICS



COMMON SHAFT

SINGLE/DUAL MAIN MOTORS
WITH POSSIBLE LOWER HP AUX. MOTOR
INTERMEDIATE GEARING WITH
DUAL GEAR REDUCERS (ONE PER SIDE)
FIG 3



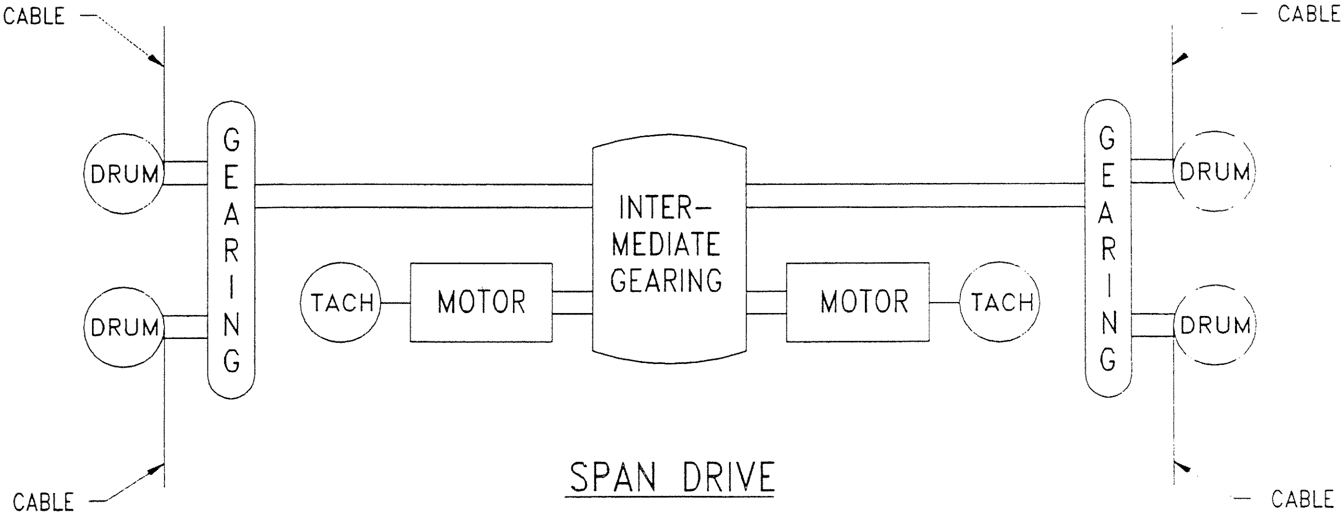
INTERMEDIATE SHAFT

2 MOTORS/LEAF (ONE PER SIDE)
DUAL GEAR REDUCERS (ONE PER SIDE)
WITH COMMON INTERMEDIATE SHAFT
FIG 4

CHICAGO STYLE

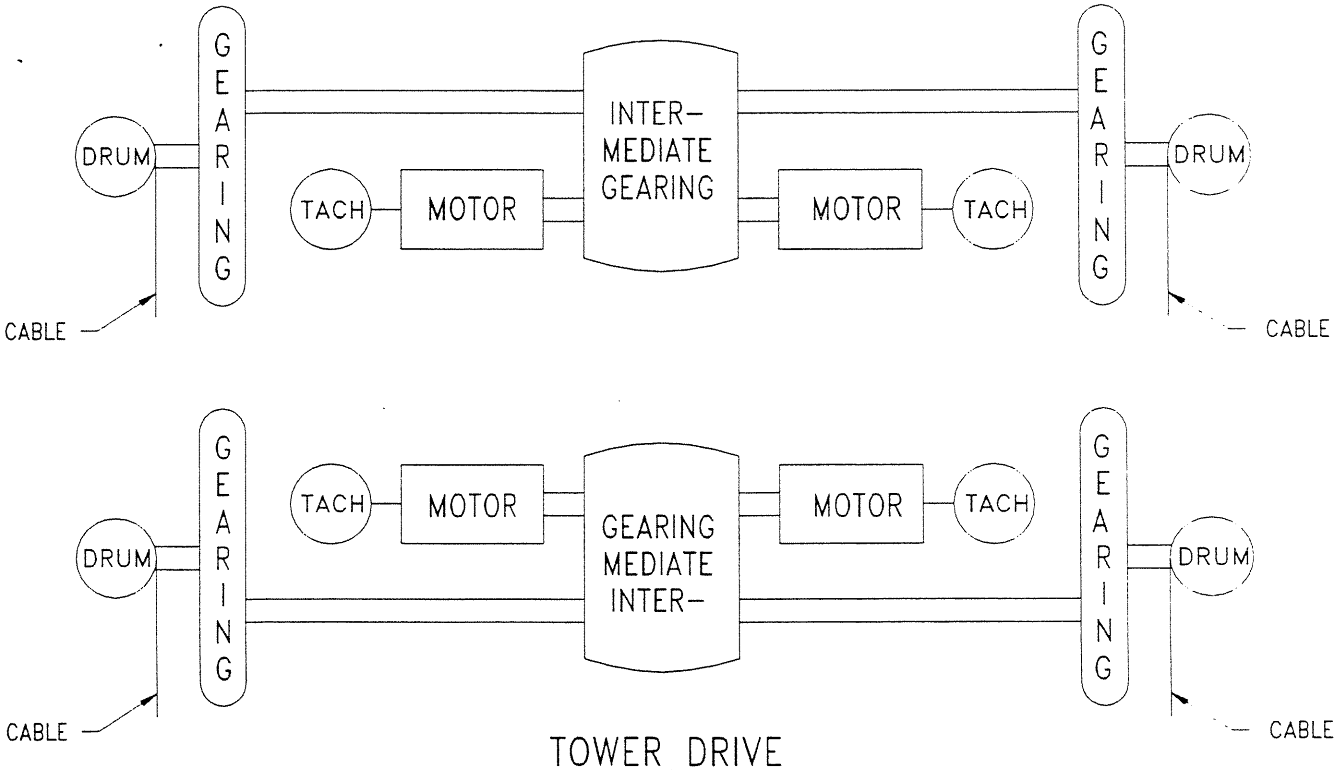
2 MOTORS/LEAF (ONE PER SIDE)
INDEPENDANT DUAL GEAR REDUCTION (ONE PER SIDE)
FIG 5

VERTICAL LIFT BRIDGE MOTOR AND GEARING SCHEMATIC



SPAN DRIVE

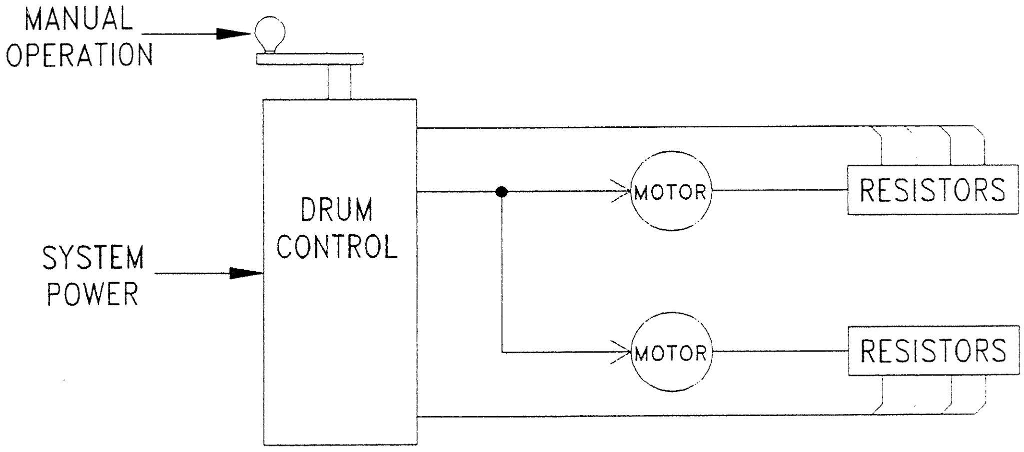
DUAL MOTOR
INTERMEDIATE GEARING WITH
DUAL FINAL REDUCERS (ONE PER SIDE OF SPAN)
FIG 6



TOWER DRIVE

4 MOTOR (2 MOTORS PER TOWER)
INTERMEDIATE GEARING WITH
DUAL FINAL REDUCERS PER TOWER
FIG 7

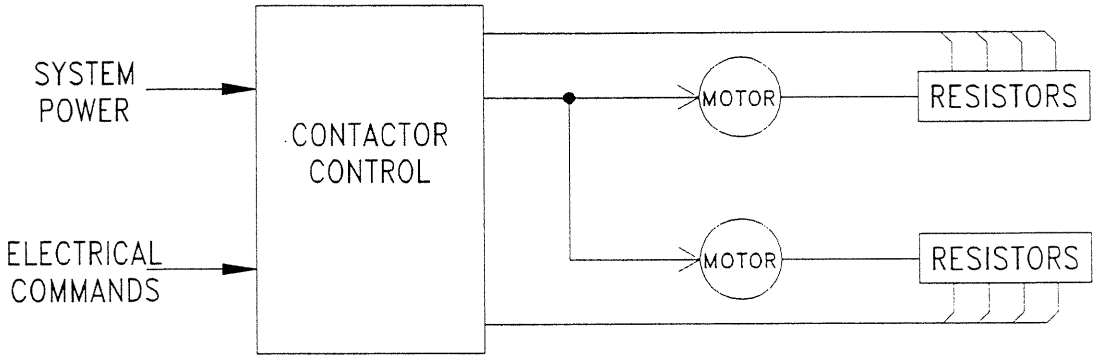
DRUM CONTROLLER



PLAIN REVERSING MANUAL CONTROL

SINGLE/DUPLEX AC MOTORS
OPERATOR COUNTER TORQUE
FIG 8

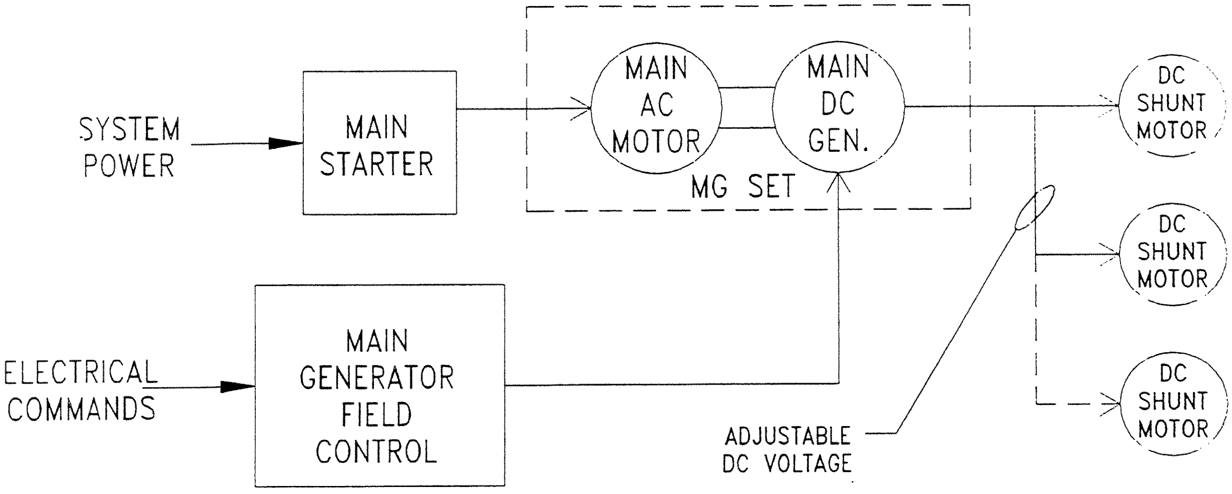
STEPPED CONTACTOR CONTROL



MANUAL/AUTOMATIC ELECTRICAL CONTROL

SINGLE/MULTIPLE AC OR DC MOTORS
AC COUNTER TORQUE OR DC DYNAMIC BRAKING
FIG 9

ADJUSTABLE VOLTAGE DC
(WARD LEONARD SYSTEM)

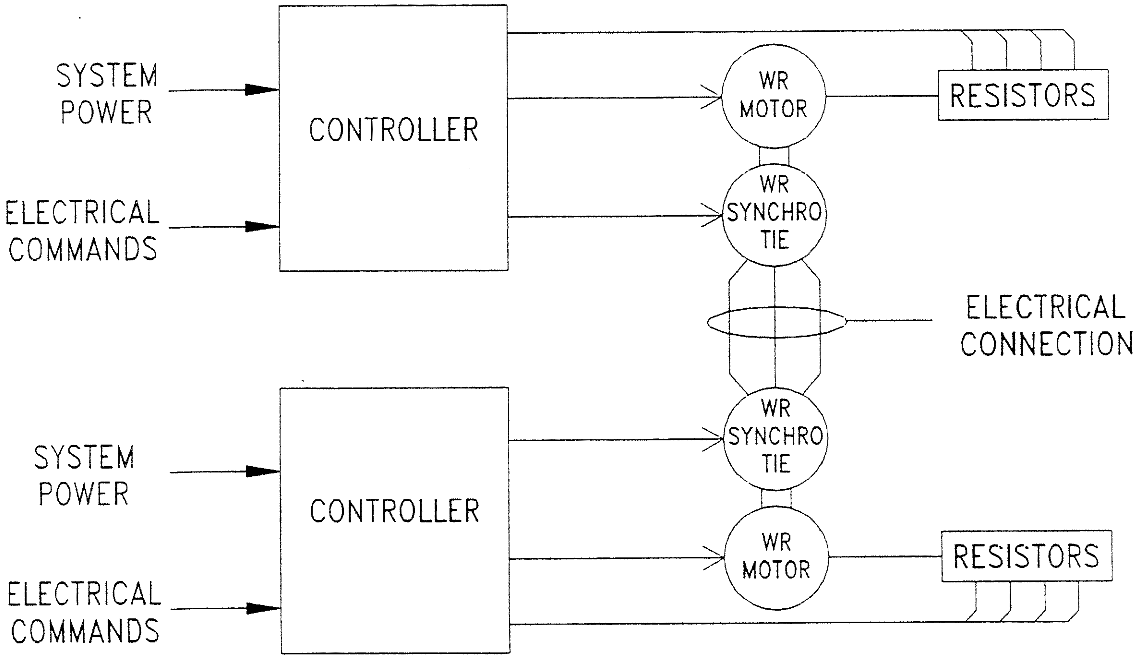


REGENERATIVE ELECTRICAL CONTROL

MULTIPLE DC SHUNT MOTORS

FIG 10

WOUND ROTOR MOTOR
(SYNCHRO - TIE)

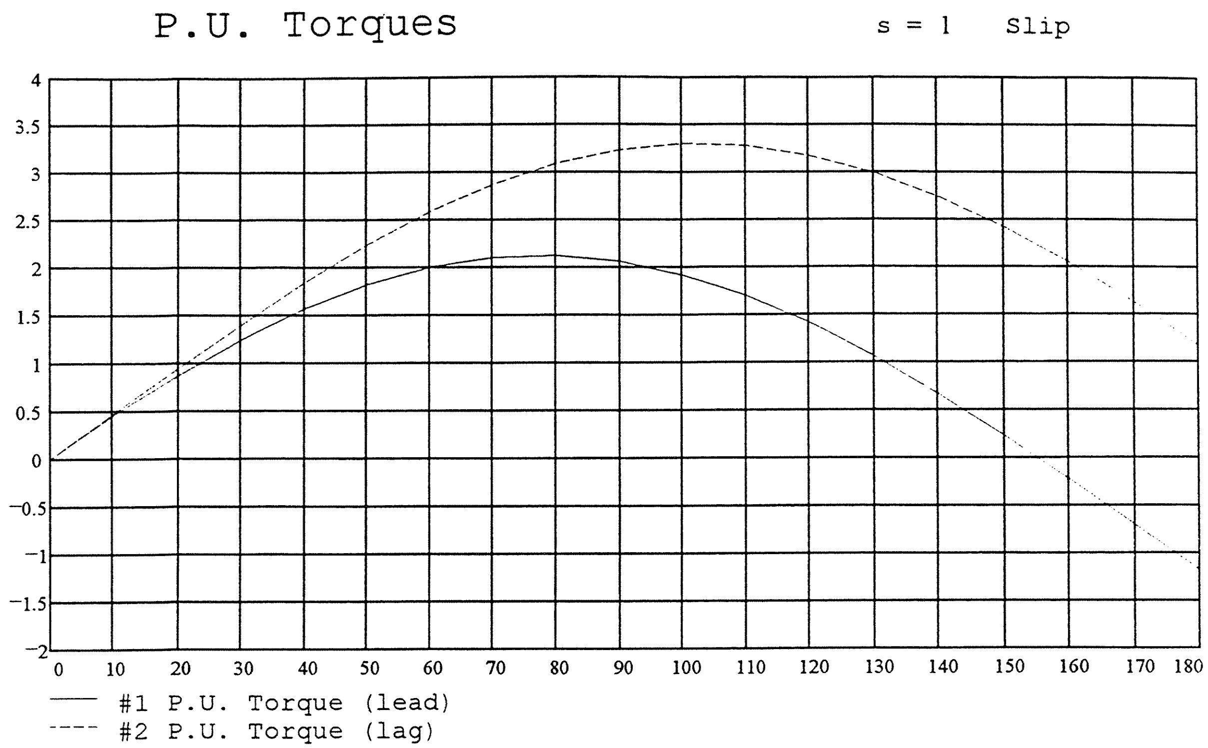


MANUAL/AUTOMATIC ELECTRICAL CONTROL

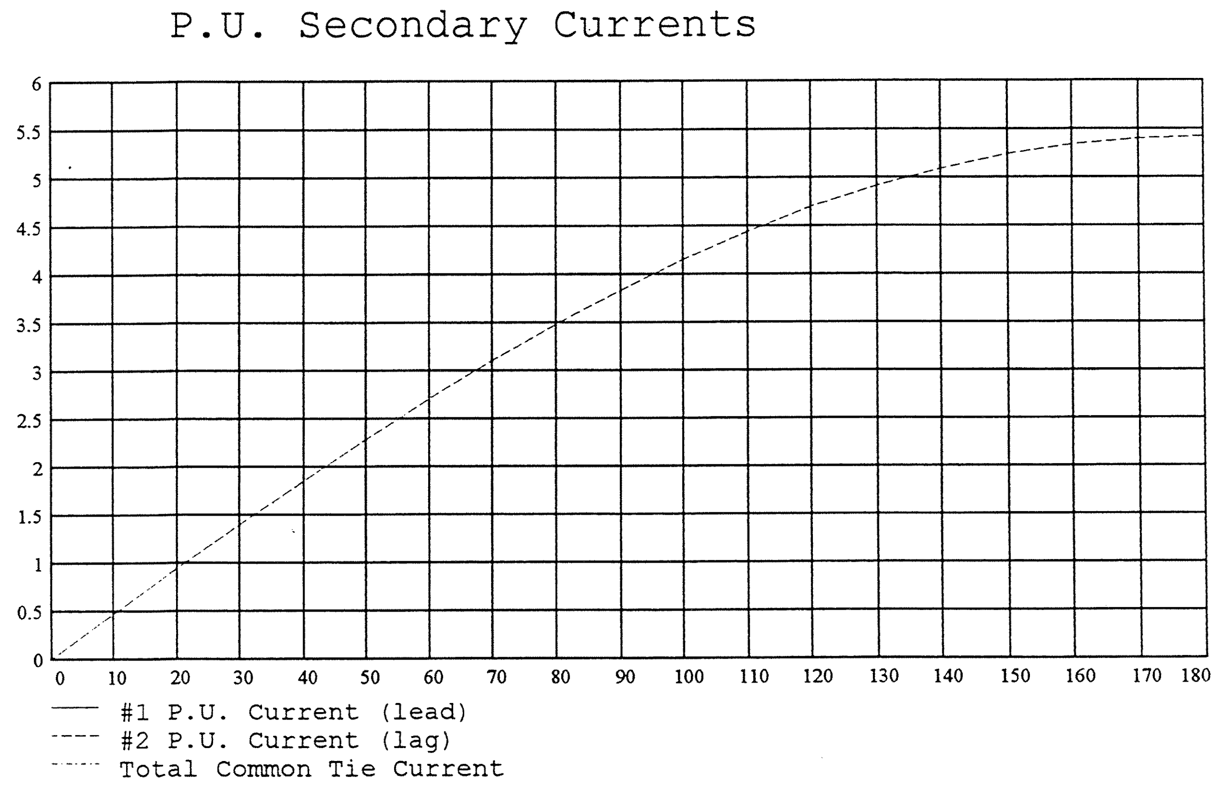
MULTIPLE AC WOUND ROTOR MOTORS

ELECTRICAL TORQUE TRANSFER

FIG 11


P.U. Torques s = 1 Slip

Displacement Angle
Fig 12


P.U. Secondary Currents

Displacement Angle
Fig 13

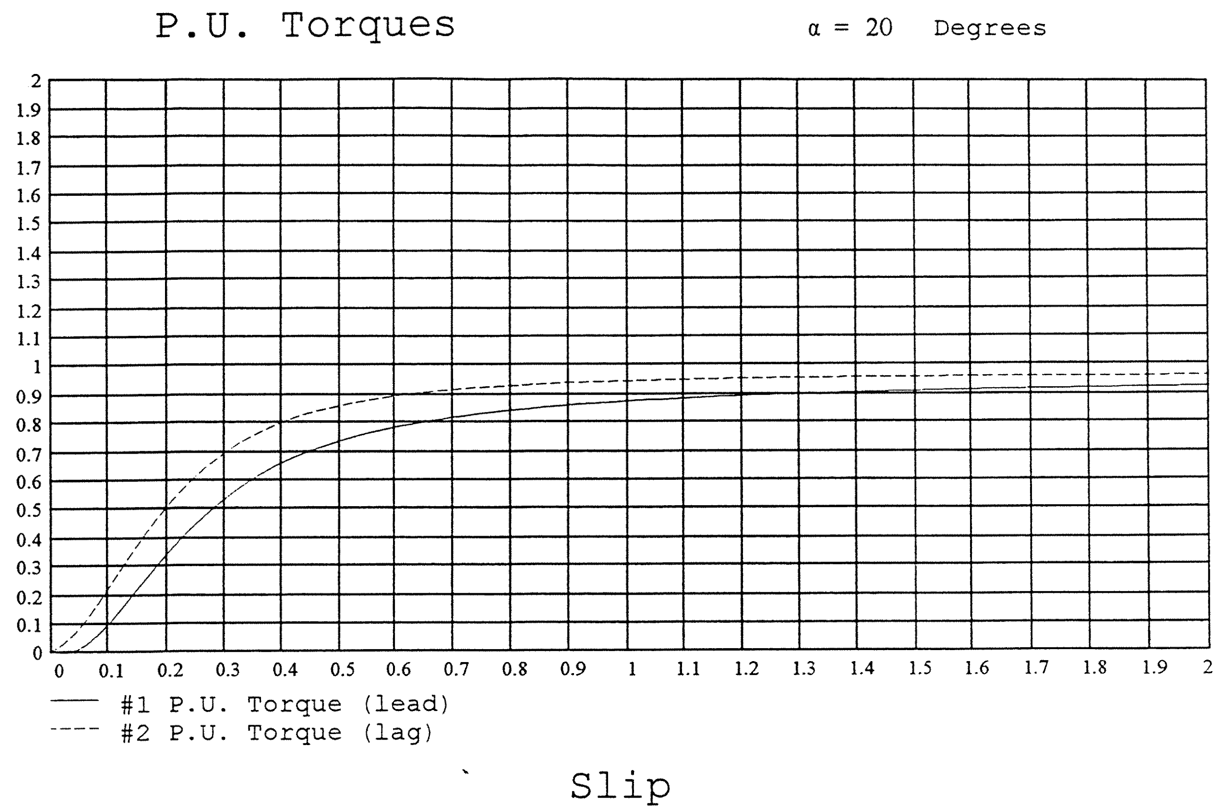

P.U. Torques
α = 20 Degrees
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2
#1 P.U. Torque (lead)
#2 P.U. Torque (lag)
Slip

Fig 14

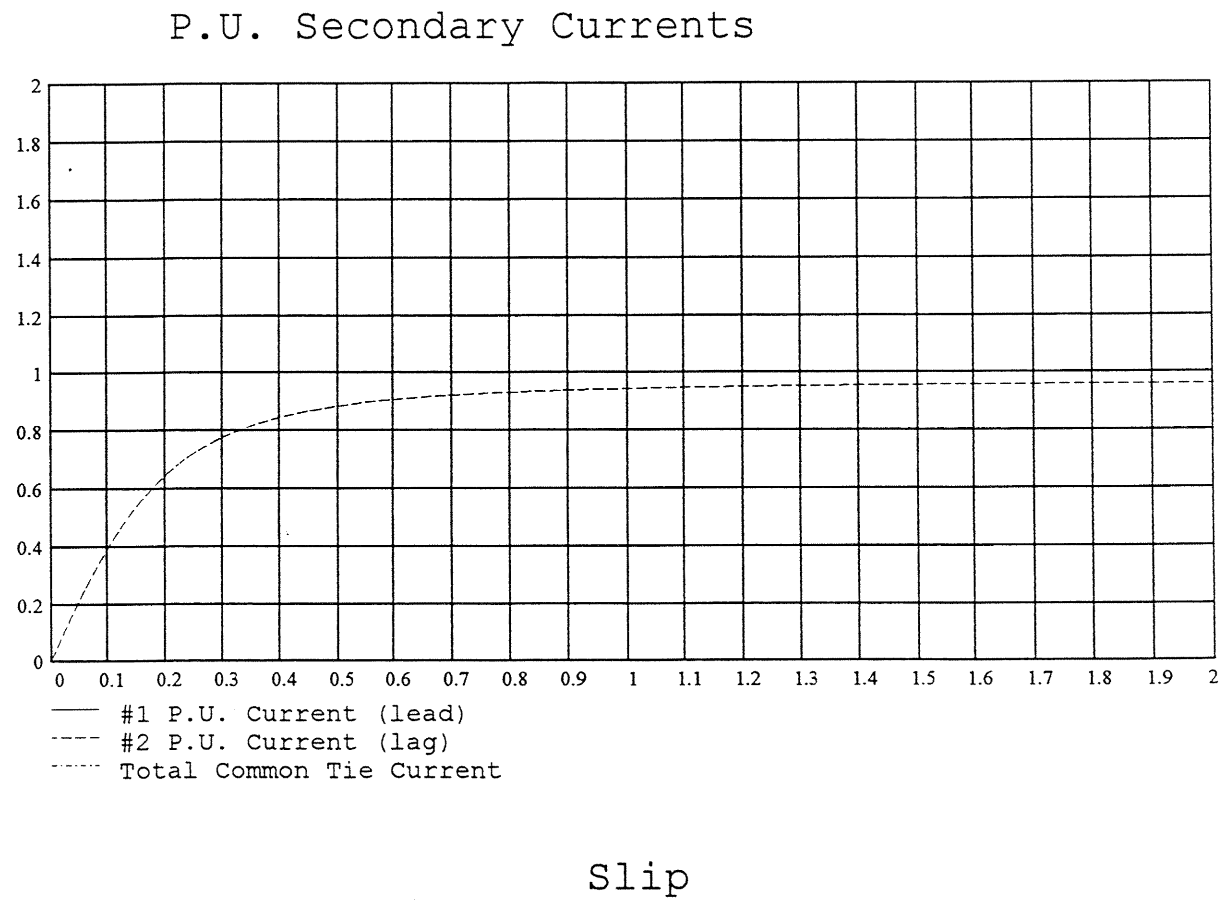
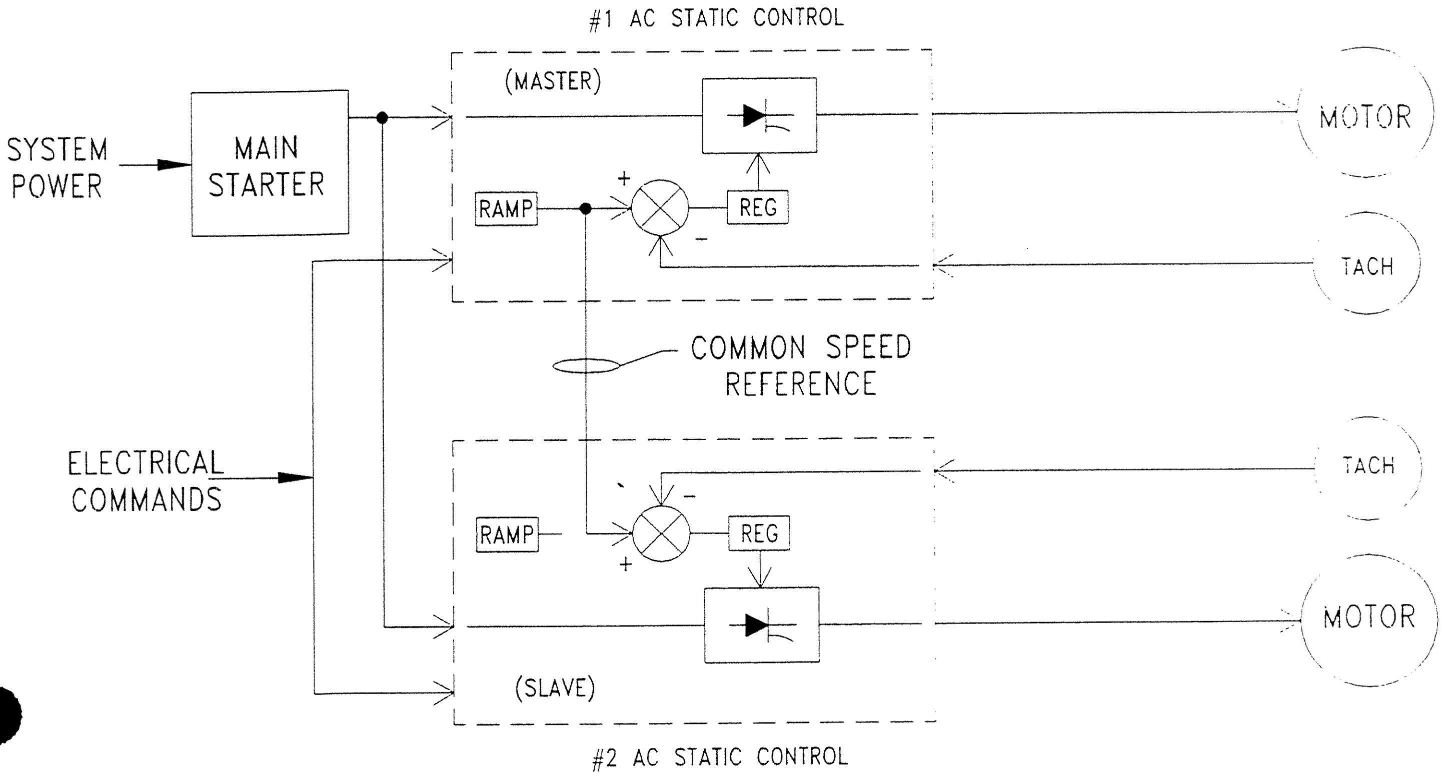

P.U. Secondary Currents
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2
#1 P.U. Current (lead)
#2 P.U. Current (lag)
Total Common Tie Current
Slip

Fig 15

AC STATIC MASTER/SLAVE CONTROL

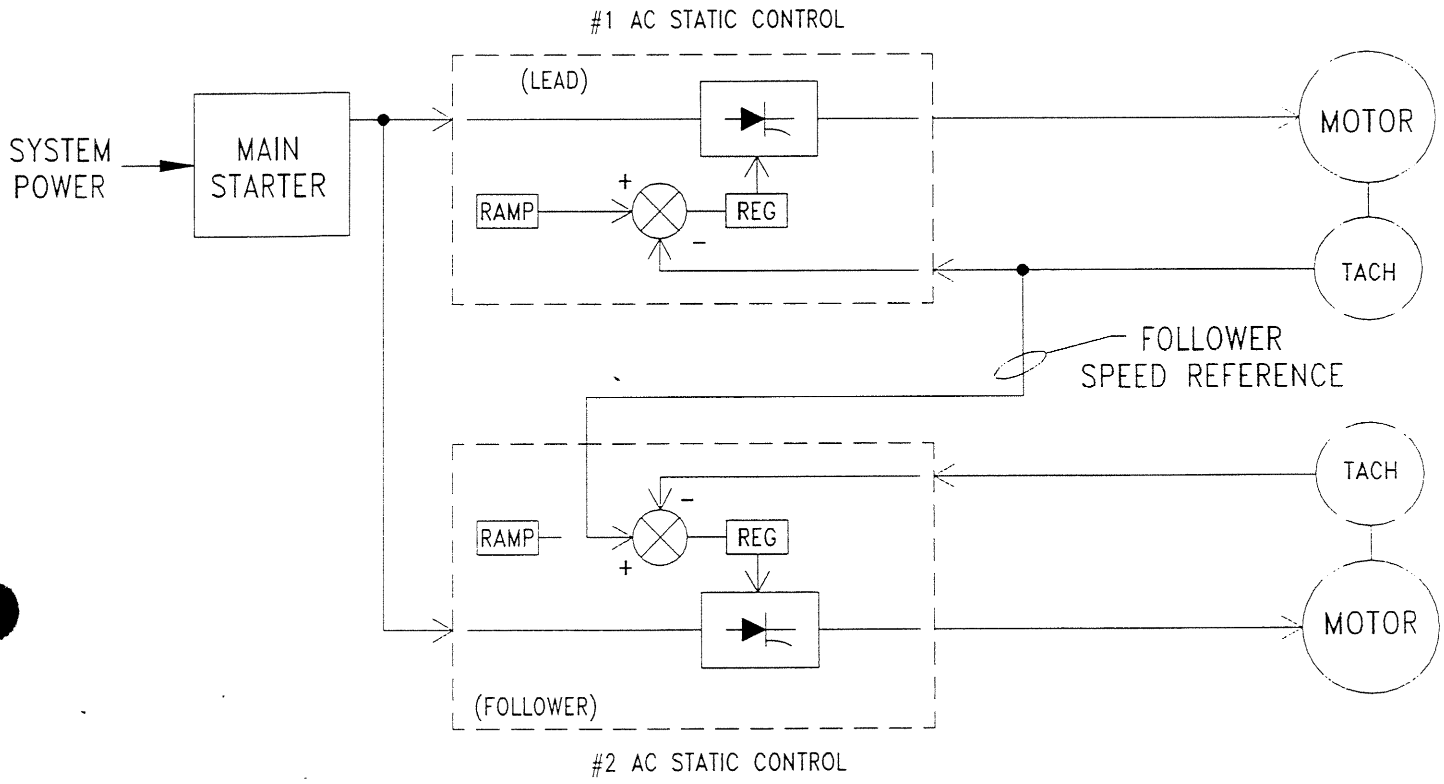


DEPENDENT PARALLEL SPEED REGULATED CONTROL

MULTIPLE AC MOTORS

FIG 16

AC STATIC TACH FOLLOWER CONTROL

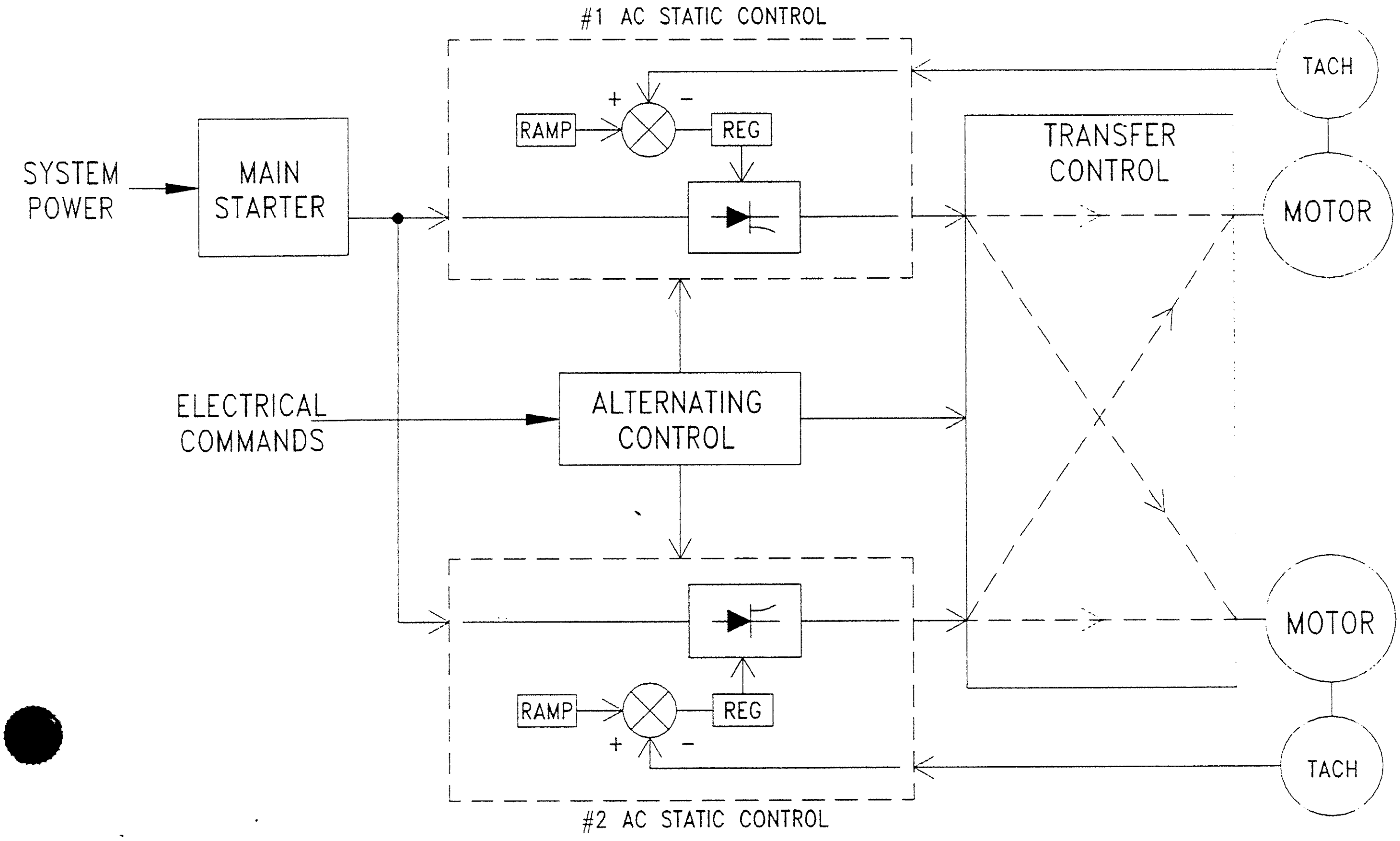


DEPENDENT ADDITIVE SPEED REGULATED CONTROL

MULTIPLE AC MOTORS

FIG 17

AC STATIC ALTERNATING DUPLEX CONTROL



REDUNDANT INDEPENDENT ELECTRICAL CONTROL

MULTIPLE AC MOTORS

FIG 18

SUMM[illegible]Y TABLE

TYPE	MECHANICS	LOAD SHARING	SPEED MATCHING	MECHANICAL REDUNDANCY	ELECTRICAL REDUNDANCY	STATIC SYSTEM CONFIGURATION
SWING	INDEPENDENT PINION	CRITICAL	NON CRITICAL	YES	AUXILLIARY SYSTEM	ALTERNATING DUPLEX OR MASTER/SLAVE
	INTERMEDIATE GEARING	NON CRITICAL	NON CRITICAL	YES	AUXILLIARY SYSTEM	ALTERNATING DUPLEX OR MASTER/SLAVE
BASCULE	COMMON SHAFT	NON CRITICAL	NON CRITICAL	YES.	AUXILLIARY SYSTEM	ALTERNATING DUPLEX OR MASTER/SLAVE
	INTERMEDIATE SHAFT	NON CRITICAL	NON CRITICAL	YES	AUXILLIARY SYSTEM	ALTERNATING DUPLEX OR MASTER/SLAVE
	CHICAGO STYLE	CRITICAL	CRITICAL	NO	AUXILLIARY SYSTEM	MASTER/SLAVE
VERTICAL LIFT	SPAN DRIVE	NON CRITICAL	NON CRITICAL	YES	AUXILLIARY SYSTEM	ALTERNATING DUPLEX OR MASTER/SLAVE
	TOWER DRIVE	INTRA TOWER NON CRITICAL TOWER-TOWER CRITICAL	INTRA TOWER NON CRITICAL TOWER-TOWER CRITICAL	INTRA TOWER YES TOWER-TOWER NO	AUXILLIARY SYSTEM OR SYNCHO-TIE	MASTER/SLAVE

FIG 19