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(54) TRANSIT VEHICLE MOTOR EFFORT CONTROL APPARATUS AND METHOD

(71) We, WESTINGHOUSE ELECTRIC CORPORATION of Westinghouse Building, Gateway Center, Pittsburgh, Pennsylvania, United States of America, a company organised and existing under the laws of the Commonwealth of Pennsylvania, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:

The present invention relates generally to application of thyristor chopper apparatus for determining the propulsion power and electric brake operations of a transit vehicle having series propulsion motors, and more particularly to control apparatus including a microprocessor that is programmed for the desired control of such thyristor chopper apparatus. The term "chopper" as used herein includes devices used to interrupt d.c. or low frequency a.c. signals at known regular intervals which can be controlled. The terms "effort" and "tractive effort" as used herein imply tractive effort or the braking effort of the motor as the case may be.

Direct current power is known to be supplied to series propulsion motors of a transit vehicle via a thyristor chopper, for e.g., as disclosed in U.S. Patent 3,530,503 of H. C. Appelo et al., for controlling the acceleration and speed of the vehicle by turning the propulsion motor current ON and OFF in a predetermined pattern. The thyristor chopper can provide either regenerative braking or dynamic braking when braking is desired.

In an article entitled "Automatic Train Control Concepts are Implemented by Modern Equipment" published in the WESTINGHOUSE ENGINEER for September, 1972, at pages 145 to 151, and in an article entitled "Propulsion Service" published in the WESTINGHOUSE ENGINEER for September, 1970, at pages 143 to 149, there is described the operation of a P signal for controlling all powered vehicles in a train to contribute the same amount of propulsion or braking effort.

In an article entitled "Alternative Systems for Rapid Transit Propulsion and Electrical Braking" published in the WESTINGHOUSE ENGINEER for March, 1973, at pages 34-41, there is described a thyristor chopper control system for propulsion and electrical braking of transit vehicles. The thyristor chopper provides a propulsion system that is superior in smoothness and enables easily maintaining a given speed, the latter feature being especially desired for automatic train control. Moreover, the thyristor system makes regenerative braking practical because the response is fast enough to continuously match regenerated voltage to line voltage, and such matching prevents variations in braking current and torque due to sudden transients in line voltage. The reduction in power consumption that results from regenerative braking can be significant, but another advantage is in relation to minimizing heat dissipation into tunnels otherwise caused by dynamic braking, where the transit vehicle passes through tunnels.

The use of presently available microprocessor devices, such as the Intel 8080 family of devices, is described in a published article entitled "Microprocessors - Designers Gain New Freedom as Options Multiply" in ELECTRONICS MAGAZINE for April 15, 1976, at page 78, and in a published article entitled "Is There a High-Level Language in Your Microcomputer's Future?" in EDN MAGAZINE for May 20, 1976, at page 62.

Reference is made herein to copending U.K. Patent Application 30013/77 (Serial No. 1587463) entitled "Transit Vehicle

Electrical Brake Control Apparatus and Method", and to copending U.K. Application 30014/77 (Serial No. 1587464) entitled "Transit Vehicle Chopper Control Apparatus and Method".

The present invention resides in a method and microprocessor apparatus for a transit vehicle electric motor having an armature operative with a power supply, said control apparatus being responsive to a signal whose magnitude depends on a required tractive effort of the transit vehicle, the apparatus comprising: means responsive to an electrical input quantity to the motor; second means to provide a control parameter to permit restriction of said electrical input quantity, and third means responsive to the second means to control another electrical input quantity to the motor.

In one embodiment, a control apparatus and method are provided for an electric motor, such as a direct current series propulsion motor used with transit vehicles, by varying the magnitude of an effort control signal RE which influences the armature current of the motor in relation to one or more operational conditions such as a drop in the power supply line voltage, the supply line current is greater than a predetermined limit or reference value, the load weighed current request becomes greater than the supply line voltage and the supply line voltage becomes greater than any one or more of a provided plurality of successively larger predetermined limits or reference values. The effort control signal which represents the tractive effort or the braking effort as the case may be is provided with a minimum value limit and a maximum value limit.

For a better understanding of the invention, reference may be had to the following description of a preferred embodiment which is exemplary of the invention and is shown in the accompanying drawing in which:

Figure 1 is a functional showing of a preferred embodiment of the present control apparatus in relation to the input signals and the output signals operative with the control apparatus;

Figure 2 illustrates the input signal operations and the output signal operations of a preferred embodiment of the present control apparatus;

Figures 3A and *3B* illustrate schematically the provided interface of the present embodiment;

Figures 4A and *4B* illustrate schematically the provided interface between the present embodiment and the controlled transit vehicle;

Figure 5 illustrates a prior art chopper logic control apparatus;

Figure 6 illustrates schematically a prior

art motor operation control apparatus;

Figure 7 illustrates schematically a prior art motoring mode of operation of the motor operation control apparatus of *Figure 6*;

Figure 8 illustrates schematically a prior art braking mode of operation of the motor operation control apparatus of *Figure 6*;

Figure 9 illustrates schematically a prior art chopper apparatus;

Figure 10 illustrates the coding of the program listing which can be used in the preferred embodiment;

Figure 11 shows a performance chart for a first actual operation of the present embodiment with a two-vehicle train and one vehicle not powered, for a normal power run without regenerative braking;

Figure 12 shows a performance chart for a second actual operation of a modification of the present embodiment with two vehicles when both vehicles are working together in power and in brake, for a fully receptive power supply line;

Figure 13 shows a performance chart for a third actual operation of a second modification with two vehicles working together in power and in brake, for a partially receptive power supply line;

Figure 14 shows a well-known operational characteristic curve for a typical series propulsion motor operative with a train vehicle and the present embodiment;

Figure 15 shows the prior art response of a propulsion motor control apparatus to a P signal; and

Figure 16 illustrates the commutative capability of the typical chopper apparatus;

Figure 17 illustrates schematically a prior art braking mode of operation for a motor;

Figure 18 shows a performance chart for a third actual operation of the present control apparatus with two vehicles working together in power and in brake, for a partially receptive power supply line;

Figure 19 shows a well-known operational characteristic curve for a typical series propulsion motor operative with a train vehicle and the present control apparatus.;

Figure 20 illustrates the here-provided limit control of the supply line voltage.

In *Figure 1* there is shown a functional illustration of the present control apparatus in relation to the input signals and the output signals operative therewith, and including a CPU microprocessor 94 operative with a PROM programmable memory 96 and a scratch pad RAM random access memory 98 used for intermediate storage. The application program is stored in the programmable memory 96. The microprocessor 94 can be an INTEL 8080, the random access memory 98 can be an INTEL 8101, and the programmable memory 96 can be an INTEL 1702 programmable read only

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memory, which items are currently available in the open marketplace. There are four illustrated categories of input and output signals relative to the controlled process operation of a transit vehicle. The digital input signals are supplied through digital input 100 from the transit vehicles and include the slip slide signal SLIP, the thyristor temperature sensor thermal overload signal THOUL, the effective value of the line filter capacitor as indicated by the fuse counter signal FUSE, the power circuit condition indication signal LCOC, the power and brake feedback signal BFEED, the field shunt feedback signal FS, the brake status signal BRKI and the clock signal 218 Hz. The analog input signals are supplied through analog input 102 and include the first propulsion motor leg current I1, the second propulsion motor leg current I2, the line current IL, the line voltage LV, the primary power request or brake request control signal P, the air pressure in the vehicle support bag members providing load weighed current request signal IRW, the analog phase signal IP and the vehicle actual speed signal S1. The digital output signals are supplied through digital output 104 to the controlled transit vehicle and include the line switch control signal LS, the power brake mode control signal P/B, the field shunt control signal FS, the first braking resistor control signal BC1, the second braking resistor control signal BC2, the third braking resistor control signal BC3, the zero ohm field shunt control signal BDC, the 10 kilometer per hour signal 10 KPH, the 25 kilometer per hour signal 25 KPH, the phase zero control signal ϕ_0 , the rate timing signal BOOST, the ON suppress control signal SUPP and the zero speed signal ZS. The analog output current request signal I+ is supplied through analog output 106 going to an analog phase controller 108 operative to supply the control signal ON to fire the chopper thyristor T1, the control signal OFF to fire the commutating chopper thyristor T2, the control signal T5 for the T5 thyristor in the propulsion motor control chopper apparatus and the analog phase indication signal IP going to analog input 102. The time period associated with turning the chopper ON and OFF is at a constant frequency of 218 Hz, that defines the clock time interval for the program cycle and for checking the process operation. During each of the 218 time intervals per second, the program cycle operates through the application program. It was necessary in the prior art for some of the input signals to be filtered to slow down the effects of noise transients and the like, but the programmed computer now samples the input signals 218 times every second; so, if desired, each signal can be checked during each program

cycle and, if the signal stays the same as it was before, a proper response can be provided. By sampling all the input signals every program cycle and by addressing every output signal every program cycle, if noise transients are received, their effect can be minimized or eliminated. For the output signals, a correct output can be given 5 milliseconds later and faster than the power response time of a train vehicle. For the input signals, digital filtering by comparison with old data can eliminate transient effects.

The train control system operative with each vehicle provides a P signal which selects a desired propulsion effort and this signal, as will be described in relation to Figure 15, which shows prior art, goes from 0 to 100 milliamps and establishes how much propulsion power or braking effort is desired by a particular train vehicle. The P signal is decoded to determine the proper motor current to generate the proper effort. In addition, there is a confirming signal, called the BRKI signal which determines when propulsion power and when braking effort is applied. The purpose of the BRKI signal is to control the power switching at the correct time to avoid one car braking while another car is in propulsion. Contact closures in the power circuitry are detected to establish that the power contacts have been made up properly and to readjust the settings in the logic. For instance, in field shunt operation, the amount of motor current is adjusted to keep from getting an undesired physical jerk for the vehicle. A failsafe reading of the P signal level is made such that, should the P signal be lost, the train control automatically goes into a brake mode. The present embodiment of the invention determines which switches to close and when to close them to modify the power circuit properly. A dynamic brake feedback signal is sent to the mechanical brake control for providing a proper combination of dynamic braking and mechanical braking necessary to maintain the deceleration level required by the P signal. The P signal is in reality a vehicle acceleration or deceleration request.

The propulsion control apparatus provides output pulses to the main power thyristors to tell them when to turn ON and when to turn OFF. When a command signal is sensed, for example, if the vehicles is in propulsion or power mode and the command signal desires the vehicle to brake, the control apparatus senses any difference between the desired motor current and the actual motor current and ramps down the actual current as required. When the current gets down to a desired level, the control apparatus opens all the propulsion switches and reconnects for a brake operation, then

ramps the motor current back up again to the level established by the desired brake operation.

5 In Figure 2 there is illustrated the input signal operations and the output signal operations of the present embodiment, including the microprocessor 94 operative with its random access memory 98 and its programmable memory 96. The analog input signals are supplied through the analog input 102, through the multiplexer 120 and analog-to-digital converter 122 and input ports 124 of the microprocessor 94 operative with a data bus 126 and address bus 128. 10 The address bus 128 and data bus 126 are operative through an output port 130 to control the multiplexer 120 and the analog-to-digital converter 122. The digital input signals are supplied through the digital input 100 operating through buffer 132 with the input port 136 operative with the data bus 126 and the address bus 128. The digital output signals are supplied through digital output 104 including output ports 140 and 142 and respective isolation circuits 144 and 146 with drivers 148 and 150 in relation to the data bus 126 and the address bus 128. 15 The analog output 106 is operative through output ports 152 and 154 through a buffer 156 and a digital-to-analog converter 158 with the analog phase controller 108.

The central processor 94 addresses a particular input port or output port or memory location and then transmits data to or receives data from that location on the data bus 126. For example, the central processor 94 can address an input port, such as input port 124 for the analog-to-digital converter 122 and the multiplexer 120. First it presents data to output 130 to tell the multiplexer 120 which analog circuit input signal is desired. Each analog signal has some sort of buffering, such as a differential amplifier or a low pass filter. When the particular input is addressed, the analog-to-digital converter 122 cycles for converting that data. The digital feedback signals from the digital feedback 100 come in and can be read whenever desired. A monitor or display panel 192 can be provided to indicate the state of operation of the central processor 94. The output port 153 is operative through digital-to-analog converter and buffer amplifier 194 with the provided test point 190 and is operative with display 192. 20 25 30 35 40 45 50 55 The manual switches 196 are operative with input port 137 as shown.

The P signal goes through the multiplexer 120 to request a particular vehicle operation. The control processor 94 senses the various currents, the various voltages and the vehicle speed. It takes digital feedback signals through buffers to know what is going on in the power circuit in relation to currents and voltages. The control processor 60 65

94 provides output command signals to the power circuit. Command signals go on the data bus and output ports function as latches so the control processor 94 can proceed to do other things while each latch remembers what is on the data bus at a given address. 70 The control processor 94 outputs a signal to close whatever power switches are desired and also outputs a requested motor current. The requested motor current is decoded in a digital-to-analog converter. The analog motor control circuit, in response to this current request, senses the actual motor current and the commutating capacitor voltage, and if everything is satisfactory, the motor control circuit appropriately fires the drivers for the chopper apparatus. 75 80

In relation to effort versus motor current, at up to about 100 amps, a typical series propulsion motor as shown by Figure 14 provides little practical effort, and above 100 amps the characteristic looks more or less like a straight line. As speed increases, there is more wind resistance, so the effective effort available is actually less; and, in braking, the reverse is true. When power is requested, the motor current comes up to the level requested by the P signal at a jerk limited rate. The vehicle increases its speed because of the effort supplied. The phase increases with speed, and when the phase approaches almost 100%, the full field operation is completed and the field shunt is used to weaken the motor field, and this provides a transient response problem; a very fast controller is required, such that it can properly control the phase on the thyristors. In actual practice, propulsion power is easier to control because in power a particular phase angle sets a percentage of line volts on the motor, and this will give a particular amount of motor current, such that if the phase is set at 50%, a particular amount of current is provided in power operation for a given speed. During braking, this same relationship is not true since brake operation is more unstable. If the phase is held at a desired place in power operation, the motor current is stable; if a particular phase setting is held in brake operation, the motor may go to overload or to zero. If it is desired to initiate brake operation, the control apparatus has to command brake which ramps down the motor current on a jerk limit, then opens up the power switches and reconnects the power switches for brake operation; thereafter, the control apparatus goes into brake operation and ramps up the motor current to give the torque necessary to get the desired brake effort. The motor may be generating a considerable voltage that goes back into the supply line so a resistor is put into the circuit to dissipate the excess voltage. As the vehicle comes down in 85 90 95 100 105 110 115 120 125 130

speed, the motor counter EMF drops and the chopper can no longer sustain the motor current, so switches are operated to change the resistors to maintain the desired motor current. If the line voltage exceeds a particular value to indicate that the line is not receptive and will not accept the generated current, the motor current is reduced if no dynamic braking resistor is used with dynamic resistors in the circuit, if the line voltage becomes excessive, the motor current is shunted into the dynamic braking resistor.

In Figures 3A and 3B there is schematically illustrated the provided interface of a chopper logic control apparatus. The digital input 100 is shown in Figure 3B operative through the buffers 132 with the input port 136. The analog input 102 is shown in Figure 3A operative through multiplexer 120 and the analog to digital converter 122 with the input port 124 of the microprocessor. The output port 130 is operative with the register 131 to control the multiplexer 120 and the analog to digital converter 122. The output port 152 is shown in Figure 3A operative with the digital to analog converter 158 and the analog phase controller 108; the output port 106 is shown in Figures 3A and 3B operative through buffer amplifiers 156 with the drivers 109, 111 and 113 for controlling the respective thyristors T1, T2 and T5. The output port 142 is shown in Figure 3B operative with the isolation amplifiers 146. The output port 140 is shown in Figure 3B operative with the isolation amplifiers 144. The output port 153 is shown in Figure 3B operative with isolation amplifiers 194 and test point 190 and operative with display 192.

The pump circuit 151 operates to verify the proper working of the present embodiment including the microprocessor 94 before the line switch is picked up and the desired propulsion motor control operation takes place. A dummy boost signal is initially generated to enable the line switch to be picked up, and during the main program operation if something goes wrong the boost signal disappears and the line switch drops out. The Y shown in Figure 10 has added to it the boost bit, and there may be waiting as shown by the code sheet; the Y carrier indicates whether the OFF suppress or the ON suppress is called for.

The load weighed current request signal is output by amplifier 153. Then the buffer 155 leads to the phase controller amplifier 157, which takes the current request signal from buffer 155 and the motor current signals I1 and I2 from lines 159 and 161. The output of controller amplifier 157 is the requested OFF pulse position or the phase angle IP. The output of the amplifier 157 is compared by comparator 163 with the timing ramp from amplifier 165 which is reset by the

computer each 218 Hz. The comparator 163 establishes when phase angle signal IP has exceeded the timing ramp, and this would determine at the output of comparator 163 where the OFF pulse is positioned. The logic block 167 determines whether or not the OFF pulse position output of comparator 163 is actually used. For example, if comparator 169 determines there is too much current in the system, the OFF pulse will be fired and might inhibit or suppress the ON pulse in logic block 171 which is operative with the ON pulse. The boost pulse comes from the computer and goes into the logic block 167 on line 173, and will fire an OFF pulse on the leading edge if comparator 169 has not already fired a pulse and suppress any further action out of the control system. The logic block 167 includes a flip-flop operative such that if an OFF pulse is fired once during a given program cycle, a second OFF pulse is not fired during that same program cycle. The power up restart circuit 175 suppresses pulses until the control system has time to operate properly. The circuit 177 is a monostable to assure that only a pulse is output, and circuit amplifier 111 drives the OFF pulse going to the gated pulse amplifier for thyristor T2. In power mode the FET switch 179 is closed to provide the desired motor characteristics compensation signal, and in brake mode, this switch is opened to provide a faster controller operation. The amplifier 181 checks the phase controller 157 to see if the signal IP is all the way up against the bottom stop to indicate too much current, and if so, the circuit 171 suppresses the ON pulses; this is used when starting up in power to skip ON pulses. The ON pulses are suppressed by the power up circuit 183. The ON pulses use the monostable 185 and the driver 109 as in the operation for the OFF pulses. The safety enable signal or pump circuit 151 will stop the firing of an ON pulse if repetitive boost signals are not provided. The FET switch 187 energizes the line switch output, such that if there is no activity on boost signal line 173, then the pump circuit 151 will cause FET switch 187 to keep the line switch dropped. The T5 signal comes from the computer to fire the T5 thyristor, and monostable 189 drives the driver circuit 191 going outside to the gated pulse amplifier for the T5 thyristor. The phase controller 108 includes the operational amplifier 157, with its attendant compensation for power and brake operations. The computer can force the controller 108 from output port 3-0 to zero for start-up. The pumping circuit 151 checks the activity of the computer by looking at the boost line 173 for snubbing the provision of ON pulses and thereby controls the line switch. If the line switch is out, the propulsion and brake

control system cannot operate the chopper apparatus, so if something is wrong, it is important to snub the ON pulses quickly, because the line switch takes time to drop out; for this reason an effort is made to stop the ON pulses when some control apparatus malfunction occurs and is sensed by the boost signals no longer being provided.

In Figures 4A and 4B there is schematically illustrated the provided interface of the present embodiment of the control apparatus. In Figure 4A there is shown the microprocessor 94 operative with the data bus 126 and the address bus 128 and the random access memory 98 and the programmable memory 96. The output ports 153, 154, 152, 142 and 140 are shown in Figure 4A. The input ports 124, 136 and 137 are shown in Figure 4B, as well as the manual switches 196 operative with the input port 137.

In Figure 5 there is illustrated a prior art chopper logic control apparatus including an analog computer 300 operative with analog input signals provided through analog input 302, with the tachometer signal passing through a frequency to analog converter 303 before going to the analog computer 300, with digital input signals provided through digital input 304 passing through digital hard-wired sequence logic 306, with the digital outputs passing through the DC to AC predrive circuit 308 and the relay drivers 309. The clock and pulse predrive circuit 310 supplies the ON, the OFF and the T5 control signals through the respective gate pulse amplifiers 312, 314 and 316 for controlling the respective thyristors in the chopper apparatus 318.

In Figure 6 there is shown a schematic illustration of a well-known prior art motor operation control apparatus operative at the present time in Sao Paulo, Brazil, as described in the above-referenced March, 1973, published article, with series propulsion motors and including a thyristor chopper. A first pair of series motors 700 and 702 and a second pair of series motors 704 and 706 are energized in parallel from the third rail connection 708.

Figure 7 illustrates the well-known motoring mode of operation of the motor operation control apparatus shown in Figure 6. The chopper 800 is used to regulate the current in the motor circuits. Turning the chopper 800 ON builds up current in the motors 700, 702, 704 and 706 by completing the circuit from DC power supply positive 708 through the motors to ground. When the chopper 800 is turned OFF, the energy stored in the motor reactor 812 and the inductance of the motors maintains current flow in the motor circuit through the loop formed by the free-wheeling diode 814. The average voltage applied to the motors is

controlled by adjusting the ratio of chopper 800 OFF time to ON time. This adjustment is made by the chopper control logic to maintain the desired average motor current and the corresponding motor torque. When operating with full voltage applied to the motors, the chopper 800 switches at the normal frequency of approximately 218 Hz with an OFF interval of about 6% of the total cycle time.

Figure 8 illustrates the well-known braking mode of operation of the control apparatus shown in Figure 6, where the motors 700, 702, 704 and 706 are reconnected by means of a power brake changeover PBC. The circuit is arranged for regenerative or dynamic braking with the motors operating as self-excited generators. The fields 902, 904, 906 and 908 are cross-connected to force load division between the paralleled generators. In regenerative braking the chopper ON and OFF ratio is regulated to maintain the desired current; the more the current provided, the more the braking. When the chopper 800 is turned ON, the current in the motors increases. When the chopper 800 is turned OFF, the current flowing in the chopper 800 is forced into the line 708 through the free-wheeling diode 814 by the motor reactor 812. The logic system for control of the chopper 800 during braking also monitors the voltage across the line filter capacitor 910, and controls the chopper ON and OFF ratio in such a manner as to prevent the capacitor 910 voltage from exceeding the line voltage 708, a condition that could result in increasing current during the chopper OFF time and loss of braking control. If the capacitor 910 voltage during regeneration reaches a preset limit, the logic removes regenerative braking by turning the chopper 800 OFF and keeping it OFF, with the remainder of the braking being achieved by friction brakes. The DC series motor acts as a series generator and inherently has a maximum generated voltage approximately twice the line voltage. To provide for the maximum energy regeneration, resistors R2, R3 and R4 are connected in series with the motors and the line by the power brake changeover PBC. The IR drop across the resistors opposes the generator voltage so that the voltage across the capacitor 910 does not exceed the voltage of supply line 708. As speed is reduced due to braking, the voltage of the series generators drops. When the ON and OFF ratio of the chopper 800 reaches the point where the OFF time is a minimum in order to maintain the motor current at the desired average value, the logic system triggers pickup of one of the shorting contactors BC1, BC2 or BC3, which reduces the IR drop in series with the generators in order that the chopper 800 can

continue to maintain substantially the same average braking current. The chopper 800 shifts from a minimum OFF condition to a minimum ON condition whenever a shorting contactor is picked up. In normal train operation regeneration of power into the power supply sometimes is not possible because of a dead third rail, loss of third rail power in the car or the absence of load being taken from the third rail. In that event the circuit consisting of thyristor T5 and resistor R1 provides almost instantaneous shift from regeneration to dynamic braking. The logic that controls the braking current makes the decision at the time of each ON pulse as to whether T5 only will be turned ON or the chopper 800 also will be fired. If the logic determines that the power supply is not receptive to regenerated energy, the chopper 800 is not turned ON and only T5 is gated to divert the motor current through the resistor R1. At the time of the next fixed ON pulse the logic again determines the need to fire the chopper 800 on the basis of power supply 708 receptivity. Only when the line 708 again becomes receptive will the chopper 800 be gated and permit the voltage generated to rise to the point where motor current again flows into the line 708.

In Figure 9 there is illustrated a well known chopper apparatus, with the chopper 800 being shown connected in the motoring mode. The first OFF pulse controls the commutating thyristor T2 and the commutating capacitor C_C charges to the same level as the line voltage; the capacitor C_C would charge to twice the line 708 voltage due to its combination with the smoothing reactor L2 if it were not for the free-wheeling diode 814. When the voltage on the capacitor C_C reaches line voltage level, the current through the capacitor C_C and thyristor T2 goes to zero and the thyristor T2 turns OFF. An ON pulse now occurs, simultaneously turning ON the main thyristor T1 and the reversing loop thyristor T3. The load is then connected directly to the supply voltage 708 causing the motor current to build up. Also the voltage across the capacitor C_C begins to decay as current flows through the thyristor T3, the reversing loop reactor L3 and the thyristor T1. The thyristor T3 turns OFF when the current reaches zero and the voltage on the capacitor C_C has reversed completely. Current is now flowing in the load only and the circuit is ready for turn-off. Turn-off is accomplished by turning the thyristor T2 ON. The load current now flows through the thyristor T2 and the capacitor C_C . After a short delay due to the inductor L2, the thyristor T1 turns OFF and the diode D4 conducts to help speed the charging of the capacitor C_C . The reactor L4 limits the rate of rise of current in the diode D4, and diode D4 stops

conducting before the capacitor C_C charges to line voltage. When the capacitor C_C is charged to line voltage, the free-wheeling diode 814 conducts current and the thyristor T2 turns OFF, leaving the circuit ready for another ON pulse and the start of another cycle. The basic operation is the same when the chopper is regulating current for motoring and for braking.

The T5 pulse controls the operation of the T5 thyristor used in the brake mode to switch in the auxiliary load resistor. When the power line is non-receptive to regenerated current, the T5 thyristor is switched to initiate dynamic braking. The braking resistors are shown as R2, R3 and R4 in Figure 8, but there could be any number of series braking resistors provided, as desired. The zero ohm field shunt in the braking mode can be operated when it is desired to short the motor fields to try to kill all of the field current and the residual magnetization of the field; in the braking mode, the field may be shorted when desired in an effort to collapse a magnetic field of the motor to stop the car from electric braking when it is desired to instead utilize the mechanical brake. The failsafe brake effort is provided for energizing the vehicle mechanical brakes and an analog control signal IP is provided for this purpose because of the fail safety requirement.

Figure 10 illustrates a code sheet that was used to develop the program listing. As shown in Figure 10 and in reference to Figure 2, output port 1 (shown in Figure 2 as 153) was used for a test mode, output port 3 (shown in Figure 2 as 154) was used for analog manipulation, output port 4 (shown in Figure 2 as 152) was used for analog command signal output, output port 5 (shown in Figure 2 as 142) and output port 6 (shown in Figure 2 divided into four bits each for 140 and 130) were used for digital command signal outputs, input port 4 (shown in Figure 2 as 136) was used for digital input data, input port 5 (shown in Figure 2 as 124) was used for analog input data and input port 6 (shown in Figure 2 as 137) was used for test purposes in relation to manual input switches.

Figure 11 illustrates a performance chart for the actual operation of the present control apparatus with the propulsion motors of a train vehicle for a normal power run. Curve 400 shows the speed of the vehicle in response to the P signal shown in curve 402. The curve 404 shows the resulting motor current and the curve 406 shows the resulting line current. Curve 408 shows an individual first motor circuit current sensed by a Hall current sensing device and curve 410 shows a second individual motor circuit current sensed by a Hall current sensing device. To illustrate that the current in-

creases at a predetermined rate with a slight tilt to compensate for the losses in the motors, the abrupt step shown in the curves 404, 406, 408 and 410 illustrates where the field shunt operation took place. When the P signal drops, as shown by curve 402, the operation changes from power to brake. The charts shown in Figure 11 are for a power run operation of two train vehicles, where one car was not powered and was pulled by the other powered car in an effort to lengthen the time response to see better what was actually taking place.

In Figure 11, the top curve 400 is obtained as the derivative of speed, with the second half actually going negative. The bottom two curves 408 and 409 show the actual outputs of the two sensors 750 and 752 shown in Figure 6. The control operation is shown in the power mode, dragging in effect one car, and shows a field shunt change, which changes the motor characteristics. When the vehicle starts operating in the motor mode the circuits are made up straight through the switches 759 and 761 shown in Figure 6. When the field shunt operates to change the motor characteristics, the center switch 759 opens and the outer two switches 763 and 765 are closed to put half the current through each of the fields 760 and 762 in relation to motors 704 and 706 and the center switch 761 opens and the outer two switches 767 and 769 are closed to put half the current through each of the fields 771 and 773 in relation to the motors 700 and 702 to result in field weakening to change the motor characteristics. The microprocessor and the hall effect devices 750 and 752 combined with the high-speed analog controller 108 provides an improved control operation with less spiking action and this means the less prone the control is to respond to an abnormal fault condition. Any increase in the spiking action means a greater probability of blowing out fuses and the like and an increased possibility of sensing a false overload condition. There is energy wound up in this inductive circuit, and when there is a change in the motor characteristics such as operation of the field shunt, the motor current has to correspondingly change very rapidly.

In relation to the performance curves shown in Figure 12, the two cars were operative with a receptive line and both energized in power and in brake so they were working together in effect as a single car operation. The vehicle speed shown by curve 420, initially increases for acceleration and then decreases for deceleration in accordance with the P signal shown by the curve 422. The line current I2 is shown by the curve 424 as the train speeds up and then goes into the brake mode, the combined motor current is shown by the curve 426 and

the individual first motor current I1 by the curve 428 and the second motor current I2 by the curve 430. When the P signal changes from power mode to brake mode, the spikes on the motor current curve 426 correspond to the closing of the various braking resistor switches.

Figure 13 illustrates performance charts for the actual operation with a partially receptive supply line of the present control apparatus with a two vehicle train. These charts show the effects of trying to have a regeneration operation without the line being fully receptive. The curve 440 shows the line voltage. This is an effort during regeneration to put as much power back into the supply line as can be practically accomplished, and this is done by raising the line voltage up to a limit. The charts shown in Figure 13 illustrate the superior performance of the present control apparatus including the microprocessor compared to prior art type of control logic apparatus for the reason that the computer program enables a better comparison of the line voltage with the generated voltage and a better control of cutting back the motor current each time the computer program cycles, which current is cut back by changing the ON-OFF ratio cycle of the chopper apparatus supplying the motor current. The prior art control apparatus cannot function in this way in that for each of the desired levels of action, depending upon the level of voltage, a different control circuit would be required.

In Figure 14 there is shown a motor characteristic for a well-known series Westinghouse traction motor of Type 1463 operative through a 5.58 to 1 gear ratio with 30 inch vehicle wheels.

In Figure 15 there is illustrated the well-known response of a prior art propulsion motor control apparatus to the P signal 30. When the P signal is below a value of about 60 milliamps, the control apparatus operates in the brake mode and for a P signal above this value of 60 milliamps, the control apparatus operates in the power mode.

In Figure 16 there is illustrated the commutative capability of a typical chopper apparatus. From a minimum level of about 10 amperes, there is a substantially linear characteristic relationship 61 between the line voltage and the commutation capability. The typical maximum requested current 63 is such that there is an excess capability 65 above this maximum requested current level 63.

Figure 17 illustrates the well-known braking mode of operation of the control apparatus, where the motors 700, 702, 704 and 706 are reconnected by means of a power brake changeover PBC. The circuit is arranged for regenerative or dynamic brak-

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ing with the motors operating as self-excited generators. The fields 902, 904, 906 and 908 are cross-connected to force load division between the paralleled generators. In regenerative braking the chopper ON and OFF ratio is regulated to maintain the desired current, with the more current providing the more braking. When the chopper 800 is turned ON, the current in the motors increases. When the chopper 800 is turned OFF, the current flowing in the chopper 800 is forced into the line 708 through the free-wheeling diode 814 by the motor reactor 812. The logic system for control of the chopper 800 during braking also monitors the voltage across the line filter capacitor 910, and controls the chopper ON and OFF ratio in such a manner as to prevent the capacitor 910 voltage from exceeding the line voltage 708, a condition that could result in increasing current during the chopper OFF time and loss of braking control. If the capacitor 910 voltage during regeneration reaches a preset limit, the logic removes regenerative braking by turning the chopper 800 OFF and keeping it OFF, with the remainder of the braking being achieved by friction brakes. The DC series motor acts as a series generator and inherently has a maximum generated voltage approximately twice the line voltage. To provide for the maximum energy regeneration, resistors R2, R3 and R4 are connected in series with the motors and the line by the power brake changeover PBC. The IR drop across the resistors opposes the generator voltage so that the voltage across the capacitor 910 does not exceed the voltage of line 708. As speed is reduced due to braking, the voltage of the series generators drops. When the ON and OFF ratio of the chopper 800 reaches the point where the OFF time is a minimum in order to maintain the motor current at the desired average value, the logic system triggers pickup of one of the shorting contactors BC1, BC2 or BC3, which reduces the IR drop in series with the generators in order that the chopper 800 can continue to maintain substantially the same average braking current. The chopper 800 shifts from a minimum OFF condition to a minimum ON condition whenever a shorting contactor is picked up. In normal train operation regeneration of power into the power supply sometimes is not possible because of a dead third rail, loss of third rail power in the car or the absence of load being taken from the third rail. In that event the circuit consisting of thyristor T5 and resistor R1 provides almost instantaneous shift from regeneration to dynamic braking. The logic that controls the braking current makes the decision at the time of each ON pulse as to whether T5 only will be turned ON or the chopper 800 also will be fired. If

the logic determines that the power supply is not receptive to regenerated energy, the chopper 800 is not turned ON and only T5 is gated to divert the motor current through the resistor R1. At the time of the next fixed ON pulse the logic again determines the need to fire the chopper 800 on the basis of power supply 708 receptivity. Only when the line 708 again becomes receptive will the chopper 800 be gated and permit the voltage generated to rise to the point where motor current again flows into the line 708.

The Figure 18 illustrates performance charts for the actual operation with a partially receptive supply line of the present control apparatus with a two vehicle train. These charts show the effects of trying to have a regeneration operation without the line being fully receptive. The curve 440 shows the line voltage. This is an effort during regeneration to put as much power back into the supply line as can be practically accomplished, and this is done by raising the line voltage up to a limit. The charts shown in Figure 18 illustrate the superior performance of the present control apparatus including the microprocessor compared to prior art type of control logic apparatus for the reason that the computer program enables a better comparison of the line voltage with the generated voltage and a better control of cutting back the motor current each time the computer program cycles, which current is cut back by changing the ON-OFF ratio cycle of the chopper apparatus supplying the motor current. The prior art control apparatus cannot function in this way in that for each of the desired levels of action, depending upon the level of voltage, a different control circuit would be required.

In Figure 19 there is shown a motor characteristic for a well-known series Westinghouse traction motor of Type 1463 operative through a 5.58 to 1 gear ratio with 30 inch vehicle wheels.

As shown in Figure 20, as the supply line voltage goes higher, the retard effort parameter RE is correspondingly increased in a stepped relationship having a digital non-linearity characteristic in an effort to provide a controlled effective asymptote limit on the supply line voltage value in the order of 890 volts in a stepped function. This operation provides a faster reduction of the retard effort parameter RE than will be recovered at the one unit every three program cycles. This increase in RE can happen in one program cycle and it can take every three cycles times nine units or 27 program cycles to reduce RE down toward zero.

As shown in Figure 18, the line voltage 440 is sensed and as it rises a BC resistor contactor shown in Figure 17 is closed which

changes the motor circuit characteristics. When the motor current rises, the line voltage starts to rise and the retard effort parameter RE functions to rapidly pull back the line current. When a BC contactor is closed, this picks up more line current because a resistor is removed from the motor circuit and the line voltage starts to rise. If the line voltage goes too high, the RE parameter function lowers the motor current and this reduces the line voltage. The power supply line is receptive to only so much current and if more current is supplied to the supply line, the supply line voltage will rise as shown by the blips in the line voltage curve 440. A very fast response is required, but a controlled operation is required to avoid a relaxation oscillator effect. The curve shown in Figure 18 relates to a partially receptive supply line that can accept only so much amperes from a decelerating train vehicle. A braking resistor that was dissipating several kilowatts of power has disappeared and the supply line cannot accept all of those kilowatts so the retard effort parameter RE function will operate to correspondingly lower the motor current and keep the system in control.

If the generated voltage in brake mode rises above a predetermined specific limit, it is not desired to put back into the power supply line a voltage greater than this limit, because in effect the regenerating vehicle is now the power supplier. The line voltage power supply includes a substation rectifier, and if the vehicle regenerated voltage is higher than what the rectifier is normally providing this can result in a shut off of the diodes in the rectifier substation.

For this reason, in effect an absolute regenerated voltage limit is established as shown by Figure 20. The regenerated voltage level and the level of current which is supplied by the train vehicle is determined by the desired brake effort, because there is a given motor characteristic as shown in Figure 19, and for any particular force or torque in the motor, a certain current level is needed and that current level also defines the voltage level. The motor characteristic for a certain braking rate shows a line called braking effort, in accordance with a specified gear ratio and the diameter of vehicle wheels, to establish a retarding force to achieve a certain braking rate. If the mass of the vehicle is known, and the deceleration rate that is desired and the number of motors are known, a calculation can be made of the brake effort force that is needed to achieve the desired rate, and this in turn establishes the current in that motor. The motor is operating as a generator giving so many amperes of current to provide a braking force of so many pounds that is needed.

The typical limit for supply line voltage is in the order of 750 volts, which is a typical voltage as seen on the third rail, and the maximum limit that is normally imposed on the regenerated voltage is 900 volts. There are usually two motors in series, so it is necessary to double the individual motor voltage. If the power circuit includes a group of two motors in series and two motor groups in parallel, about 750 volts is provided by each motor, so about 1500 volts is provided by the two motors. To lower this voltage and as shown in Figure 17, the braking resistors R2, R3 and R4 can be inserted in series with the generating motors to absorb some of the excess voltage. The power or energy that the motor is generating is converted into heat through an IR drop provided between the generating motor and the chopper and the line, which absorbs the additional and excess voltage.

The above assumes that the supply line receives regenerated energy from the vehicle; however in some instances the supply line cannot receive any energy from the vehicle. For example, if the vehicle is going along the track and goes, from one substation area into another substation area, where there is a break in the third rail connection, all of a sudden within a fraction of a second the supply line cannot receive any of the energy that the vehicle has been supplying. A basically inductive system is wound up supplying energy, and the line no longer can receive this energy. If the supply line will take no regenerated energy from the vehicle, the generated current starts charging the line capacitor and starts rising. The generated voltage is compared with the permitted highest limit that is allowed; for example, 900 volts can be the absolute limit. To have a control region of 50 volts, the control point is moved down 50 volts, to give a permitted limit of 850 volts. If the generated voltage goes above this 850 volt limit, the present control apparatus takes a voltage sample for each program cycle and provides an immediate response if a bigger voltage than the desired limit is sampled. If a voltage above the limit is sensed, depending on how far above it is, a progressive cutback is provided, depending on the magnitude of the voltage sample and how big the voltage sample is above the control limit of 850. The control apparatus will accumulate the action that is taken in accordance with the difference amount that the sample voltage is above the limit voltage. In the confirmed brake mode of operation CYCBB, each cycle of the program the supply line voltage is sensed and compared to this provided limit of, for example, 850 volts. If the line voltage is greater than a first limit of 850 volts then the retard effort RE is increased to be RE plus

two. If the line voltage is greater than a second limit, for example 860 volts, then the retard effort RE is set to be RE plus two plus three. If the line voltage is greater than a third limit, for example 870 volts, then the retard effort is made RE plus two plus three plus four. If the sensed line voltage is greater than a fourth limit, for example 880 volts, then the retard effort RE is set to be RE plus two plus three plus four plus five. If the sensed line voltage is greater than a fifth limit, for example 890 volts, then a total suppression of ON pulses is provided. The program performs this operation in time sequence. The value of RE determines the reduction of the motor current. When the sensed supply line voltage is below the first limit of 850 volts, the motor current is at a satisfactory level and follows the current request without modifying the retard effort parameter RE for subtraction from that current request. The desired brake signal expressing a certain amount of braking effort is developed into a current request, and the retard effort RE is subtracted away from it during the next program cycle. The so modified current request determines the phase angle of the chopper which is controlling motor current every program cycle. The external high-speed analog phase controller shown in Figure 1, as soon as this current request is received by it, takes immediate action to move the chopper phase angle in accordance with the desired motor current. By controlling the time the chopper is ON, the control apparatus changes the motor current. The motor is operating as a generator and there is much inductance in this circuit including the motor reactor. When the chopper is ON it provides effectively a short across the generator circuit to put the generated voltage across the inductance and the resistance of the circuit to determine the rate of change of current. When this chopper shuts OFF, then the supply line voltage responds to the generated voltage from the motor. The average voltage across the chopper is established by the ratio or percentage of time the chopper is ON in relation to the time the chopper is OFF. The retard effort RE is one of the factors that is used to make this ratio, and in addition the ratio is a function of speed, the current request, and the like.

To control the chopper apparatus, the present control operation is sampling the generated voltage to determine the ON-OFF ratio of the chopper; an averaging is going on in relation to a current request, a P signal, a motor current level, the vehicle speed and so forth to get an average; then when the line voltage rises above a predetermined limit as determined by sampling every program cycle, a predetermined pattern of cutbacks on the current request is

provided in a cyclic and accumulative action, with the last step being when the line voltage is greater than a last predetermined limit and the control apparatus suppresses the ON pulses to inhibit turning the chopper ON for each program cycle that the latter condition prevails and with the chopper OFF the motor current keeps dropping.

The prior art control approach was to fire the T5 thyristor, if the line voltage rose above a predetermined level, by comparing the line voltage with an absolute reference such as 850 volts; it was an analog control with filtering and as the line voltage started increasing the control started turning ON the T5 thyristor shown in Figure 17. One control comparison was made to control the chopper and a second control operated with a higher limit than 850 volts to control turning ON the T5 thyristor. The present control operation stays with and eventually will turn OFF the chopper if desired, and this is important relative to energy conservation, because as soon as the T5 thyristor is turned ON this loses into the resistance all the energy that is available from the motor circuits. Normally the power supply line is capable of taking some amount of energy, since even a single car has an air-conditioner, an air-compressor and can absorb a certain amount of energy even by itself.

WHAT WE CLAIM IS:-

1. Microprocessor control apparatus for a transit vehicle electric motor having an armature operative with a power supply, said control apparatus being responsive to a signal whose magnitude depends on a required tractive effort of the transit vehicle, the apparatus comprising:

means responsive to an electrical input quantity to the motor;

second means to provide a control parameter to permit restriction of said electrical input quantity; and,

third means responsive to the second means to control another electrical input quantity to the motor.

2. Control apparatus as in Claim 1, wherein said one electrical input quantity comprises voltage of the supply line to the motor, and said another input quantity comprises motor-current.

3. Control apparatus as in Claim 2, wherein said second means comprises a chopper and wherein said control parameter is provided by a comparing means which compares the motor supply voltage with a selected limit to restrict the motor current depending on the selected limit.

4. Control apparatus as in Claim 1, wherein said second means comprises means for providing an effort-control-parameter to permit restriction of the armature current of said motor, the apparatus

additionally including:

means for determining a value of said effort control parameter in relation to a predetermined operational condition; and,

5 wherein said third means comprises:
means responsive to said effort request signal and said effort control parameter for controlling the armature current of said motor.

10 5. The control apparatus of Claim 4, with said determining means being operative to compare the voltage of said power supply with a predetermined reference for reducing the value of said effort-control-parameter when said voltage is less than said predetermined reference.

15 6. The control apparatus of Claim 4, with said determining means being operative to change the value of said parameter in accordance with a predetermined time characteristic.

20 7. The control apparatus of Claim 4, with said predetermined operational condition being the voltage of said power supply.

25 8. The control apparatus of Claim 4, with said predetermined operational condition being the current provided by said power supply.

30 9. The control apparatus of Claim 4, with said determining means being operative to compare the current provided by said power supply with a predetermined reference for increasing the value of said effort-control-parameter when said current is greater than said reference.

35 10. The control apparatus of Claim 4, including means for establishing a maximum value and a minimum value on said effort-control-parameter.

40 11. The control apparatus of Claim 4, with said armature current controlling means providing a motor current request signal in accordance with a predetermined relationship between said effort request signal and said effort control parameter for controlling said armature current.

45 12. The control apparatus of Claim 4, with said armature current controlling means providing a motor current request signal in response to said effort request signal and said effort control parameter; and,

50 means for modifying the value of said effort-control-parameter in accordance with a predetermined relationship between said motor current request signal and the voltage of said power supply.

55 13. The control apparatus of Claim 4, with said determining means providing a reduction in the value of said effort-control-parameter by a comparison of said operational condition with each of a plurality of successively larger predetermined references.

60 14. A method of providing tractive

effort control for a transit vehicle electric motor having an armature and operative with a power supply and an effort request signal representative of a required tractive effort using a microprocessor, comprising 70 the steps of:

providing an effort control parameter to limit the armature current of said motor; modifying the value of said effort control parameter in relation to an operational condition of said power supply; and,

75 controlling the armature current of said motor in response to said effort request signal and the modified value of said effort control parameter.

80 15. The method of Claim 14, with said step of modifying the value of said effort control parameter being also operative to compare a predetermined reference with said operational condition.

85 16. The method of Claim 14, with said operational condition being the voltage of said power supply.

90 17. The method of Claim 14, with said step of modifying the value of said effort control parameter being in accordance with a predetermined time characteristic.

95 18. The method of Claim 14, with said operational condition being the current provided by said power supply.

19. The method of Claim 14, including the step of establishing a maximum limit and a minimum limit on the value of said effort control parameter.

100 20. The method of Claim 14, including the step of establishing a motor-current-request-signal for controlling the armature current of said motor in accordance with a determined relationship between said effort request signal and said effort control parameter.

105 21. The method of Claim 14, with said step of modifying the value of said effort control parameter providing respective reductions in the value of said effort control parameter by a comparison of said operational condition with each of a plurality of successively larger predetermined references.

115 22. Microprocessor control apparatus for an electric motor as claimed in Claim 1 and substantially as described hereinbefore with reference to the accompanying drawings.

120 23. A method of providing effort control for a motor, as claimed in Claim 14 and substantially as described hereinbefore with reference to the accompanying drawings.

RONALD VAN BERLYN

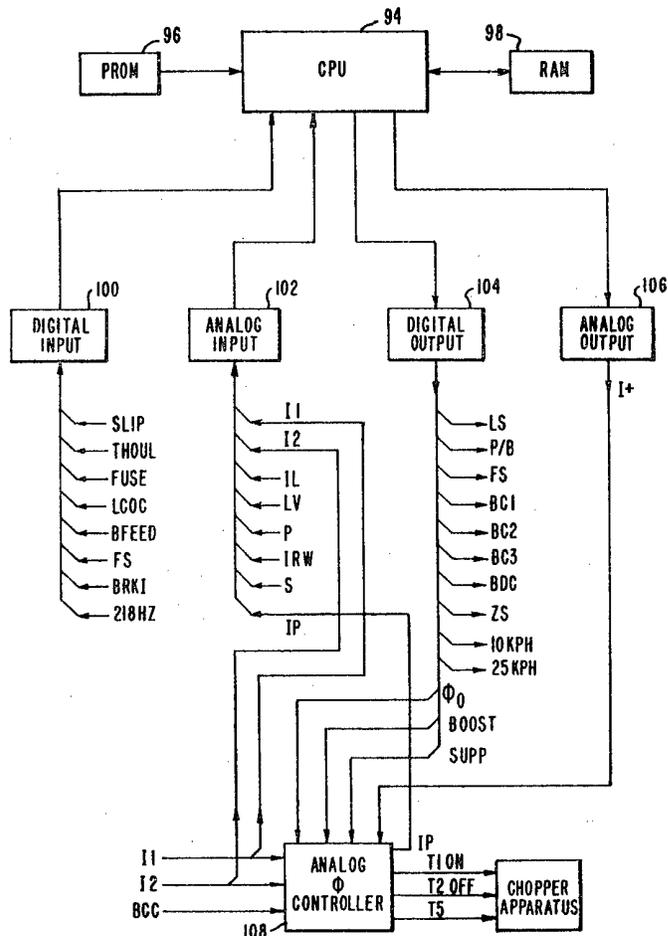
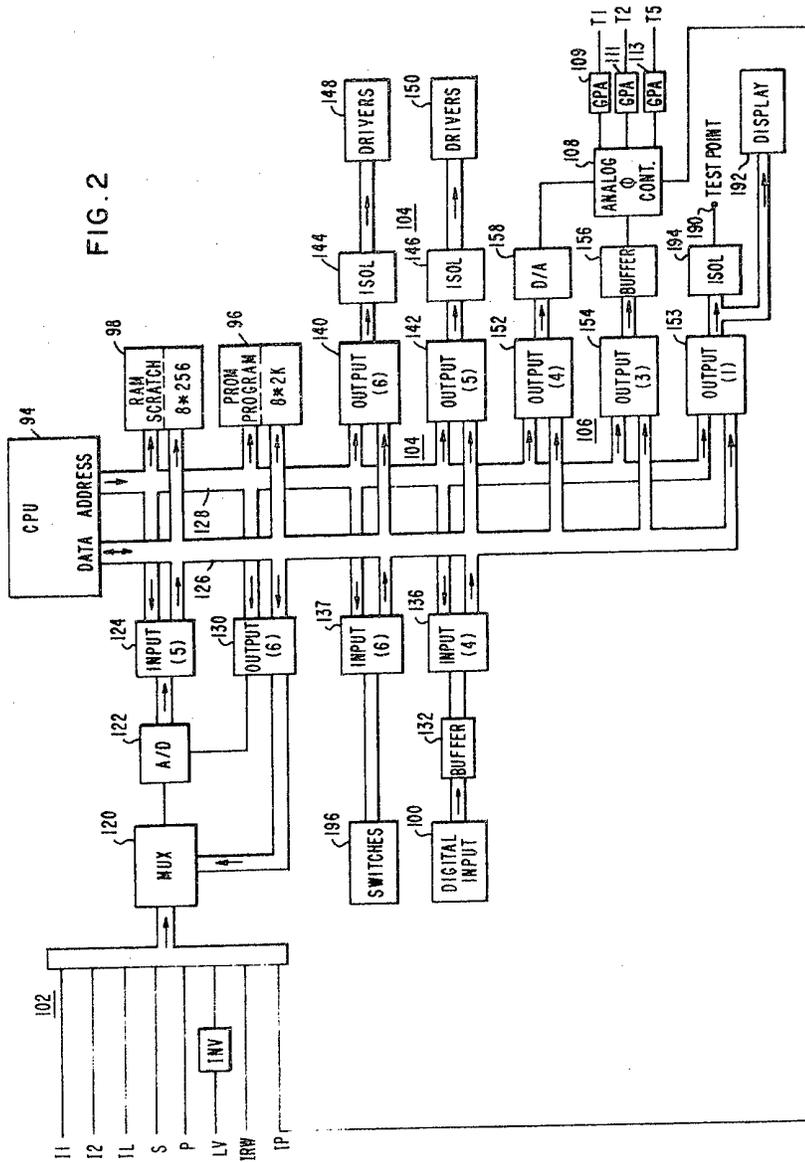
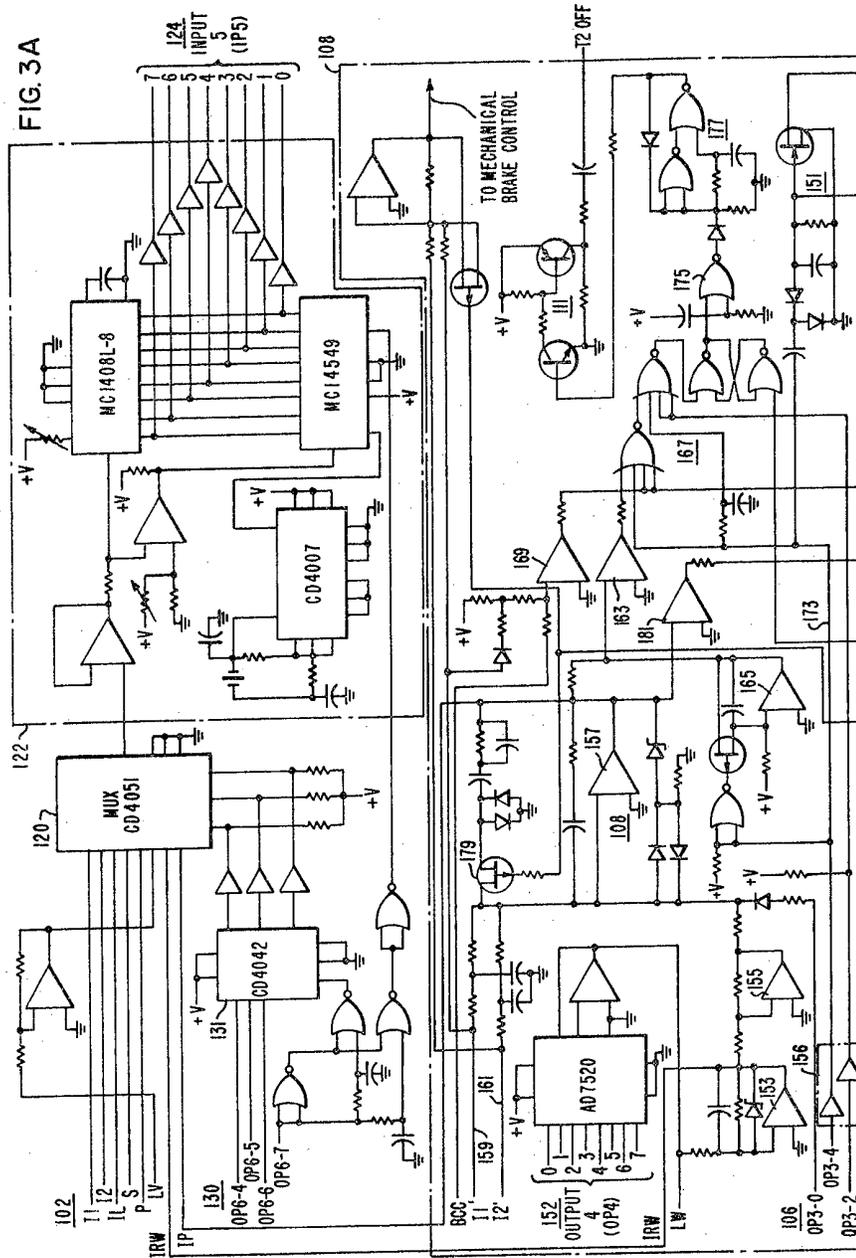


FIG. 1





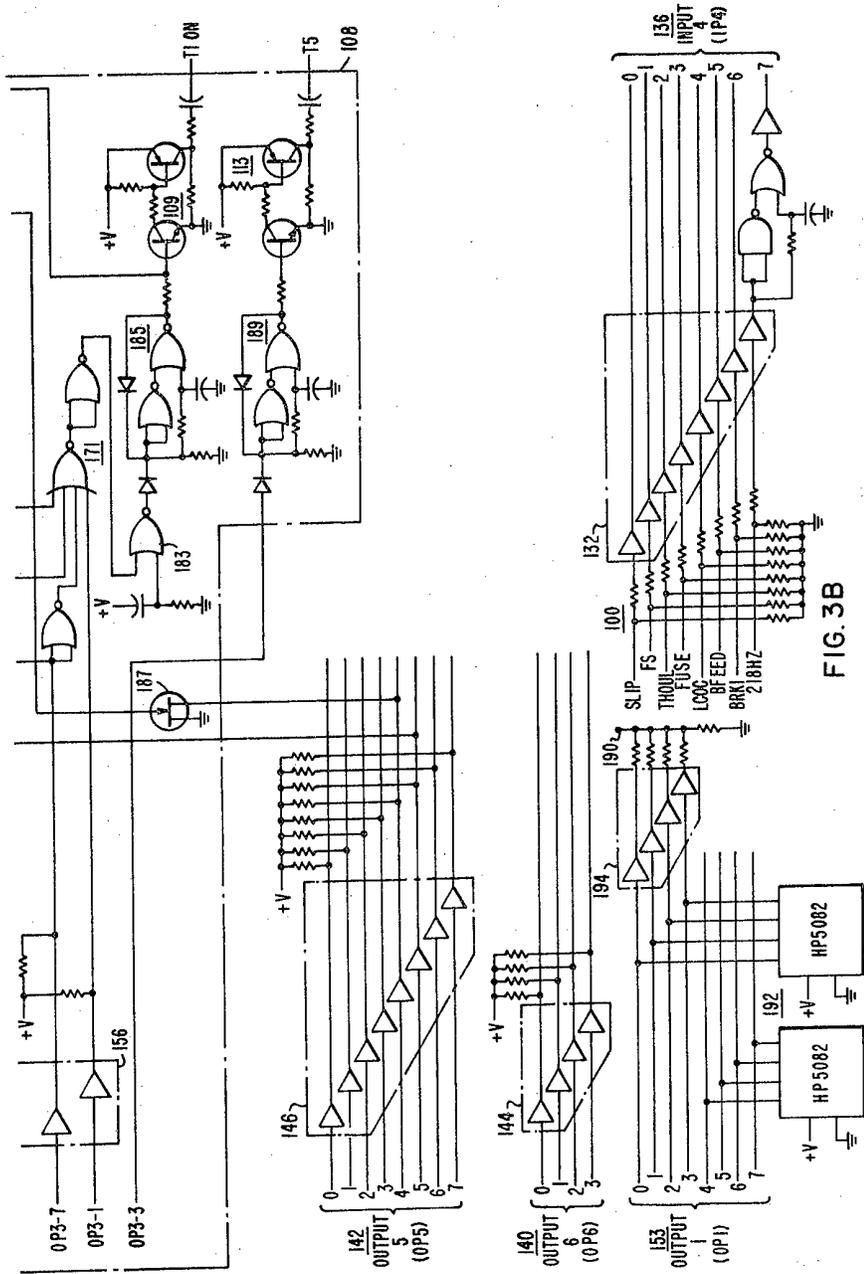


FIG. 3B

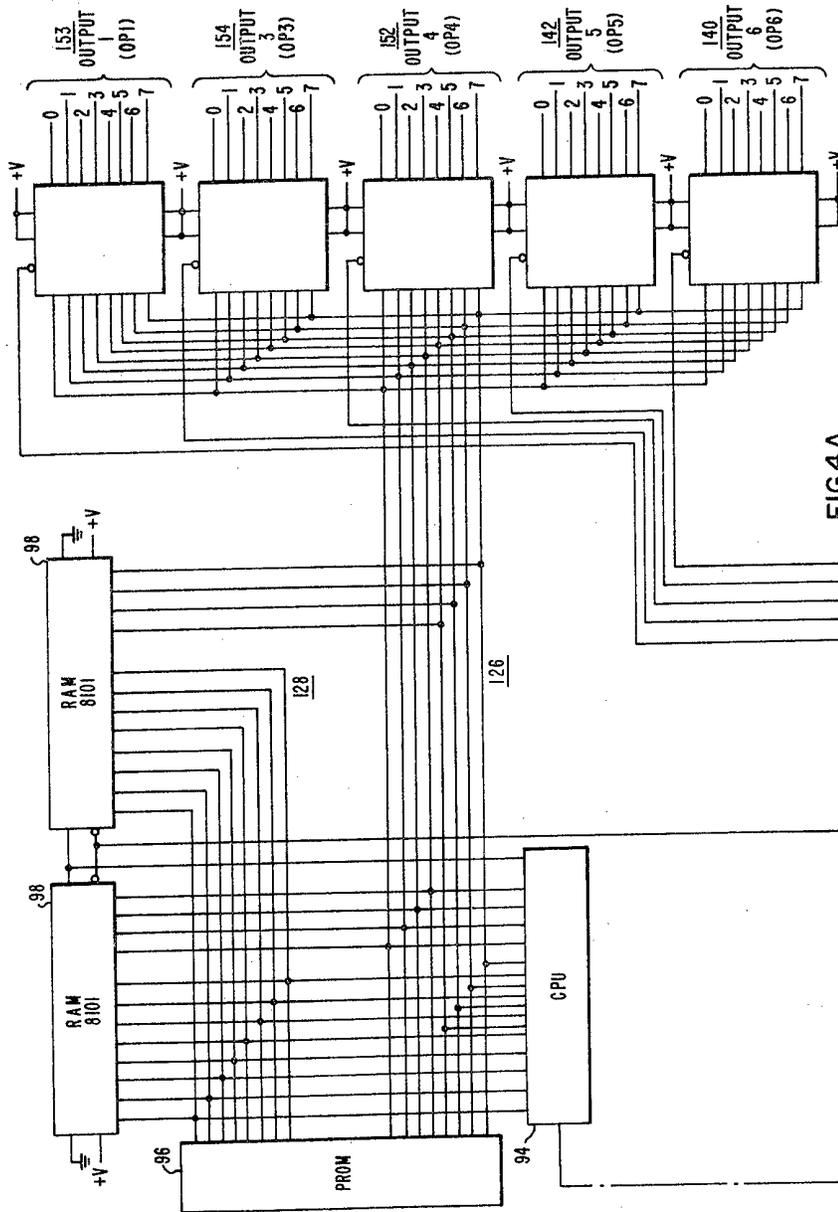
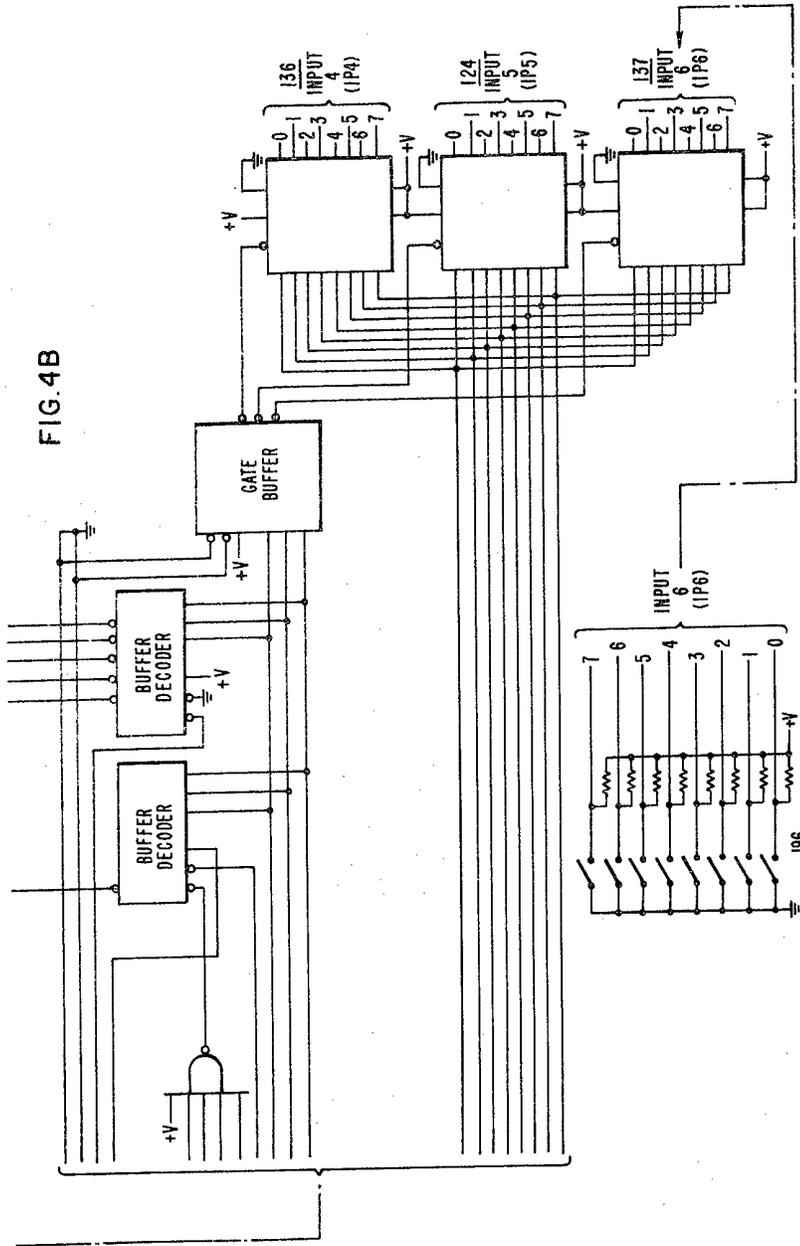
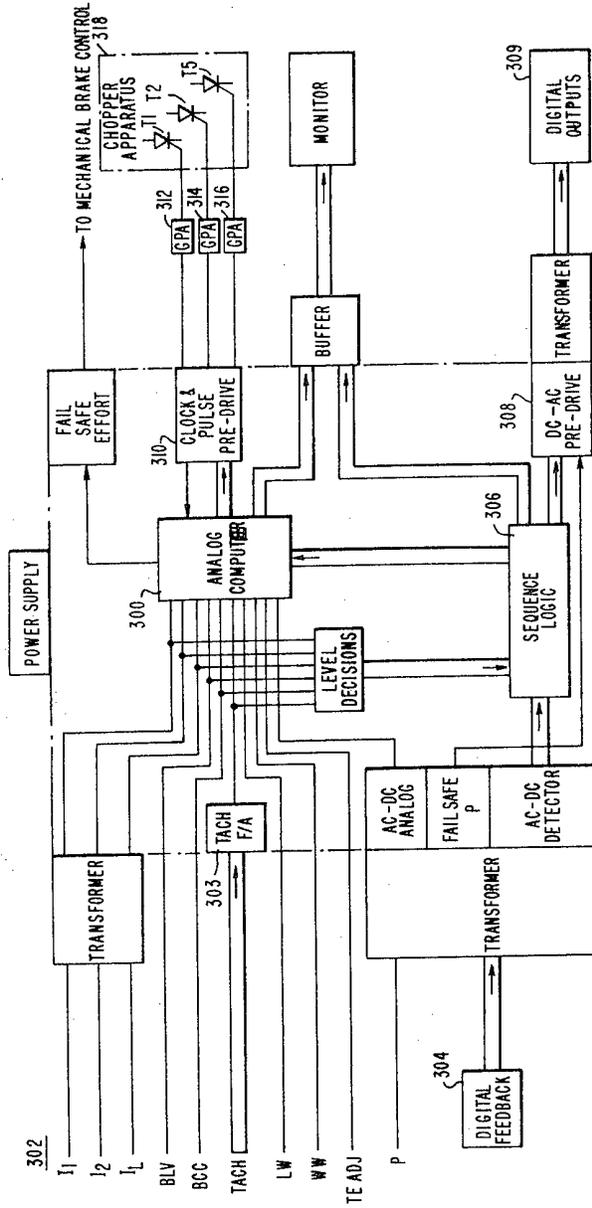


FIG 4A

FIG.4B





PRIOR ART
FIG. 5

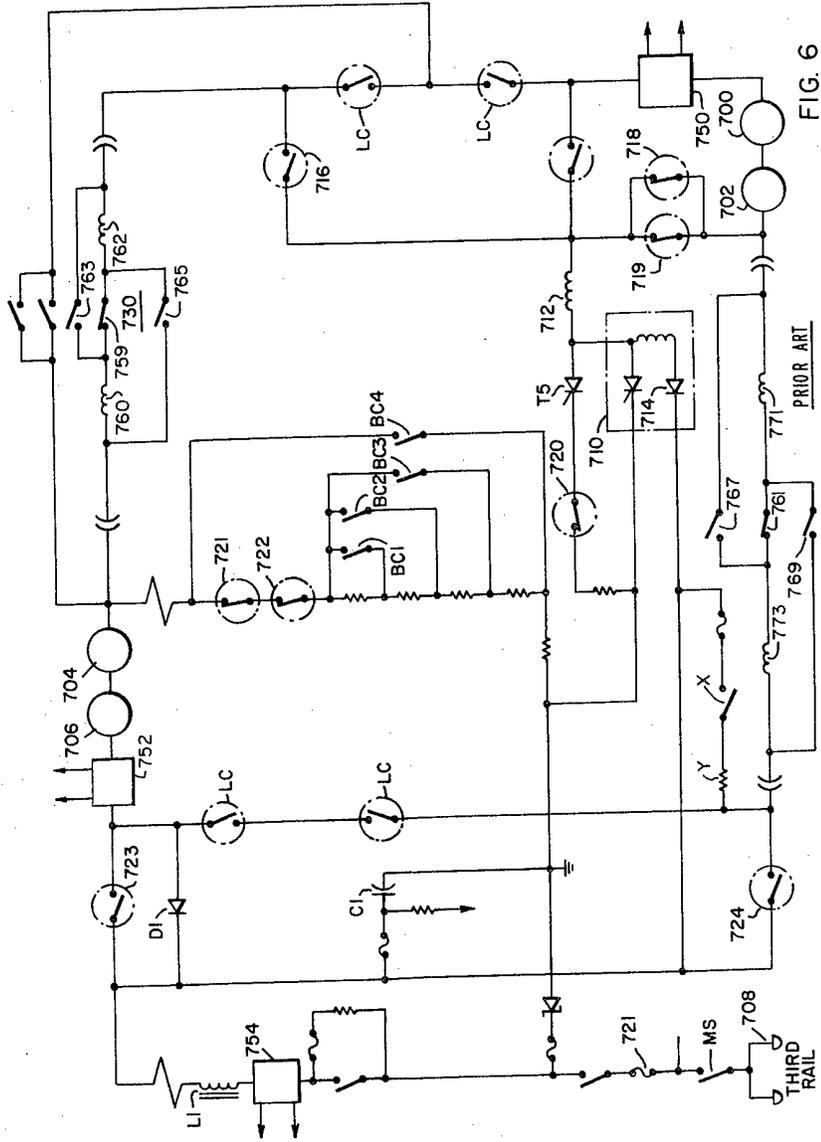


FIG. 6

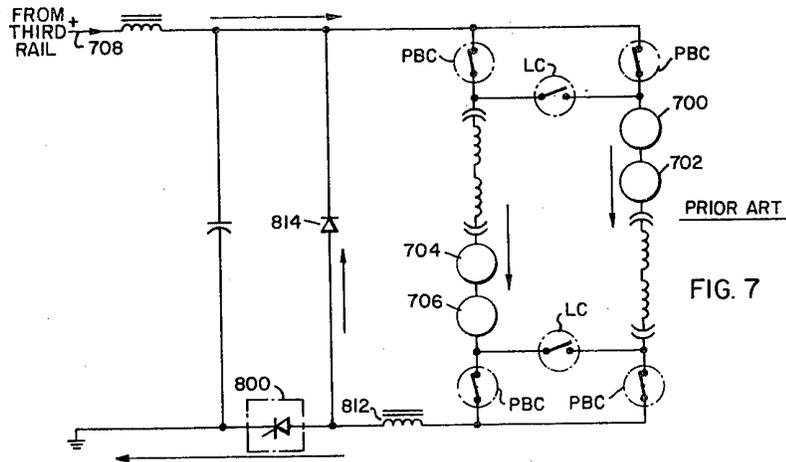


FIG. 7

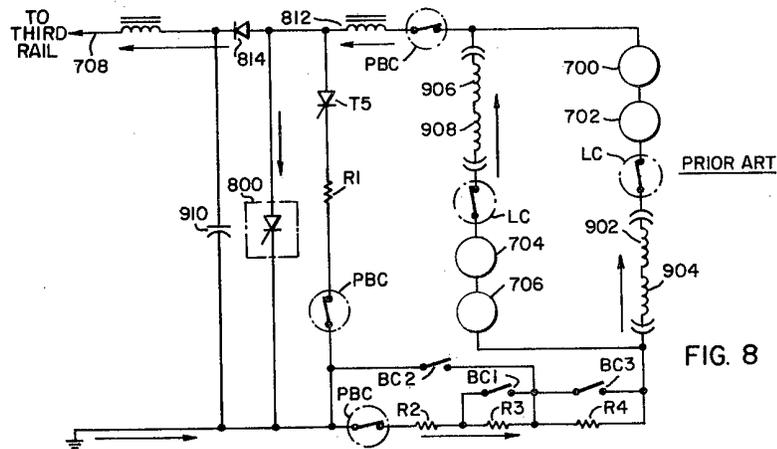


FIG. 8

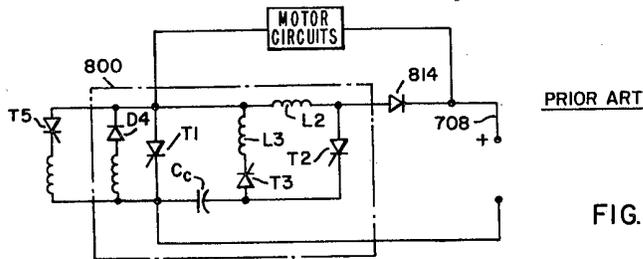


FIG. 9

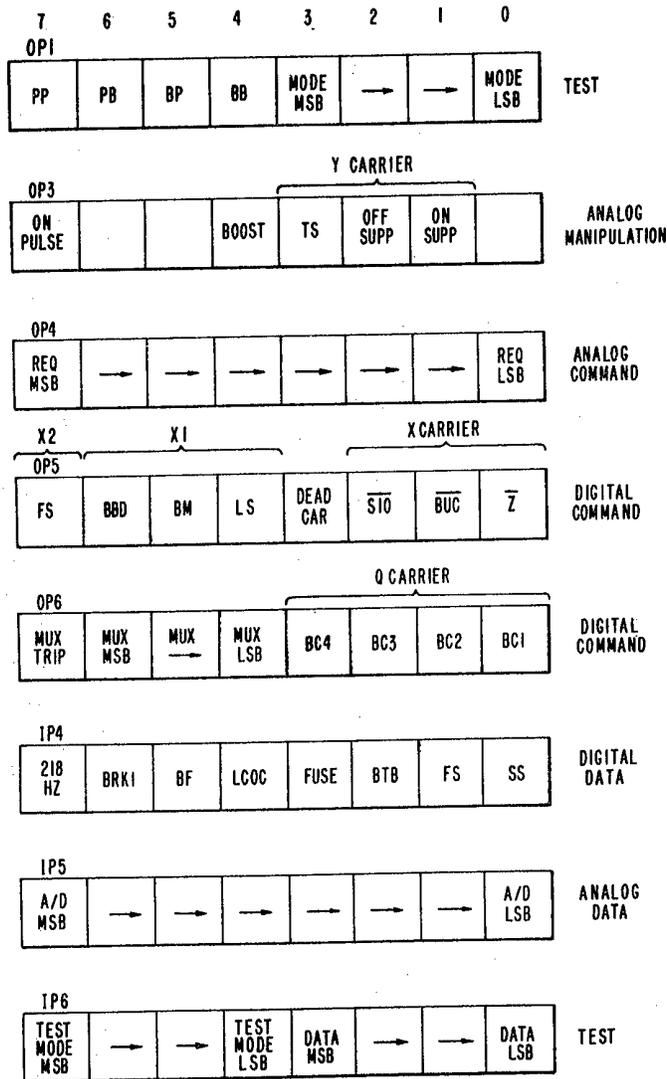


FIG. 10

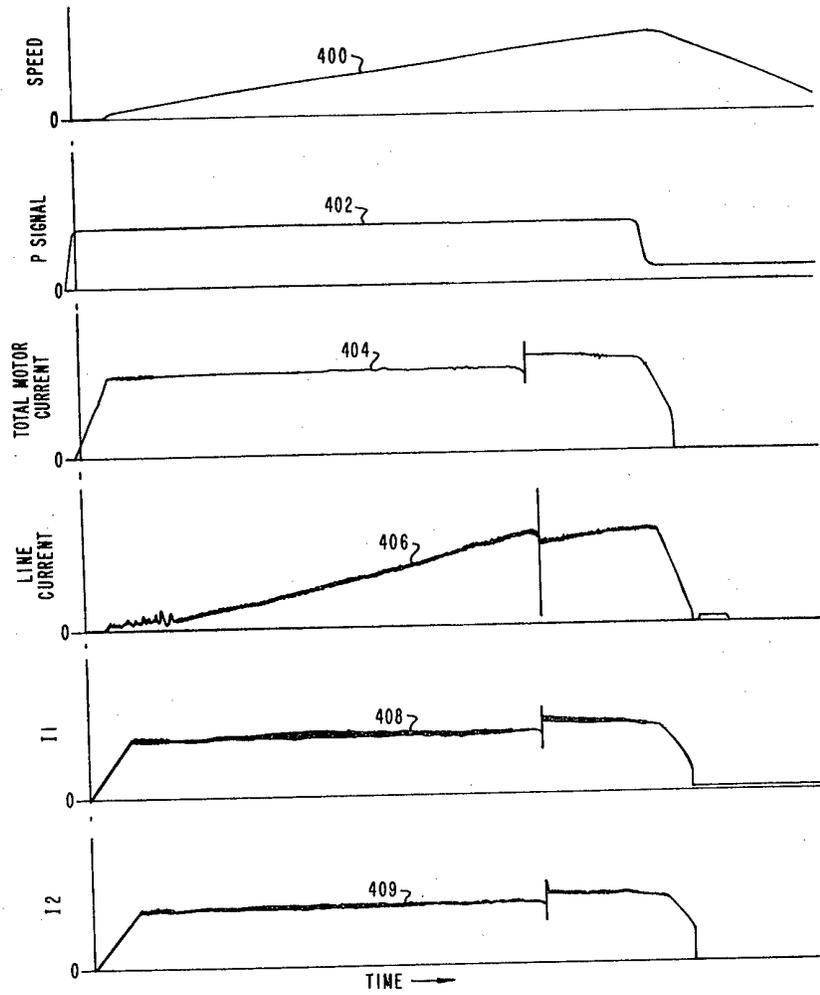


FIG. II

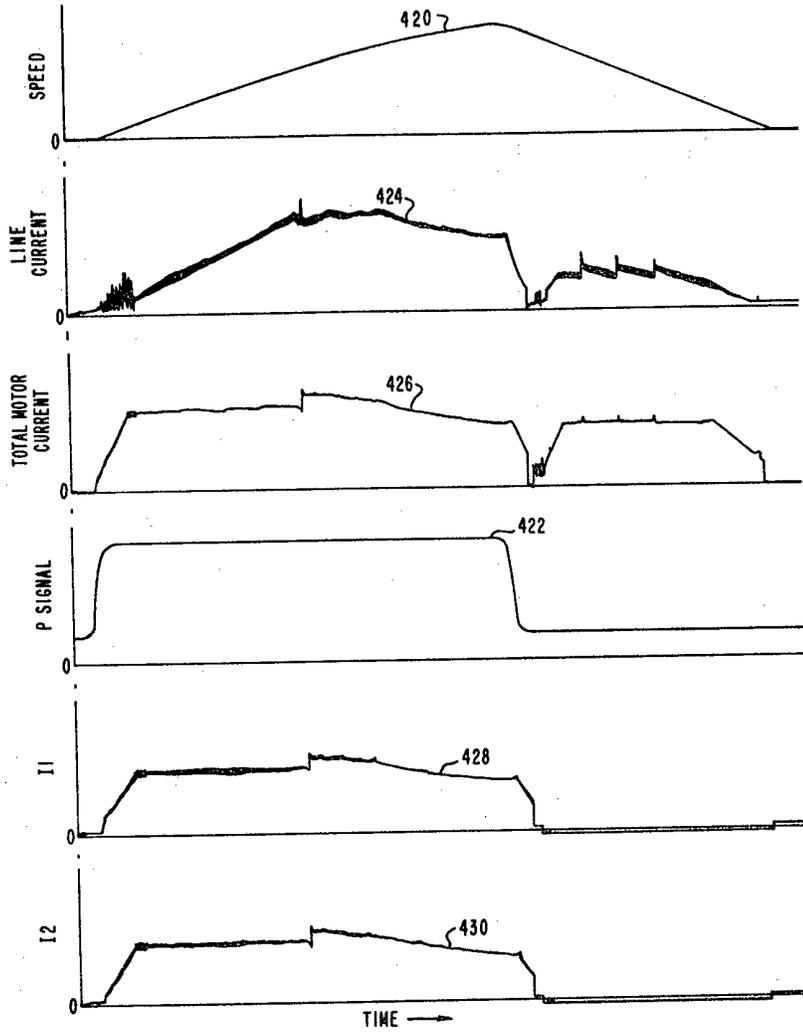


FIG. 12

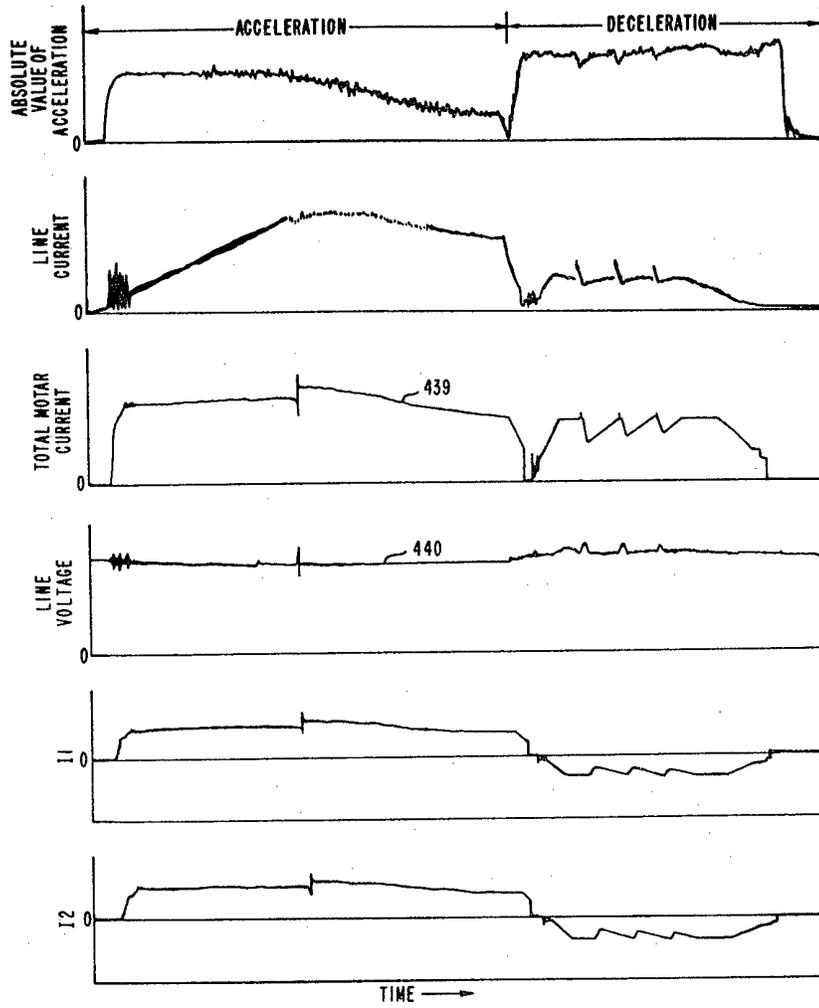


FIG. 13

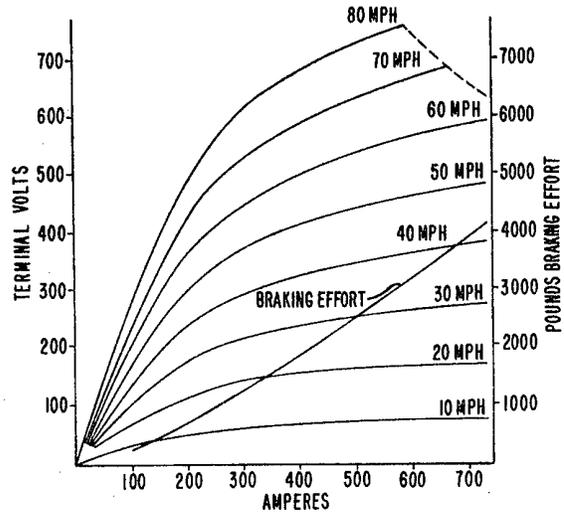


FIG. 14

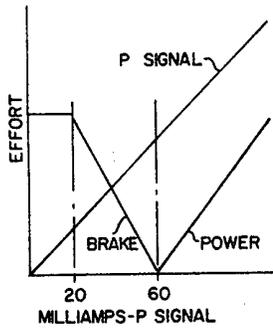


FIG. 15

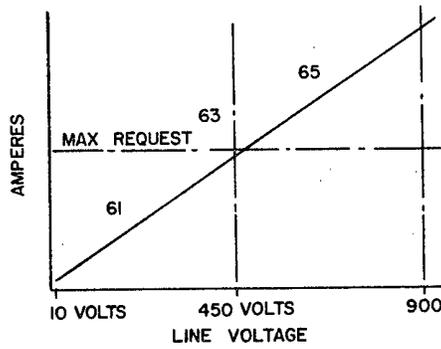


FIG. 16

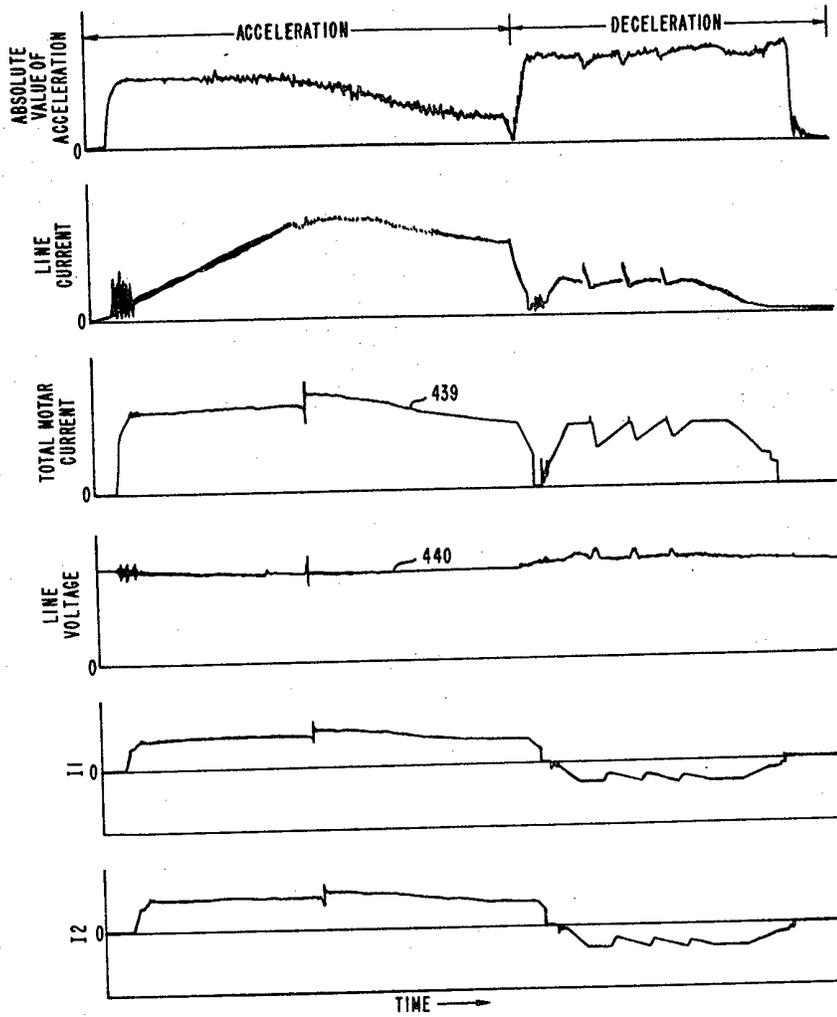


FIG. 18

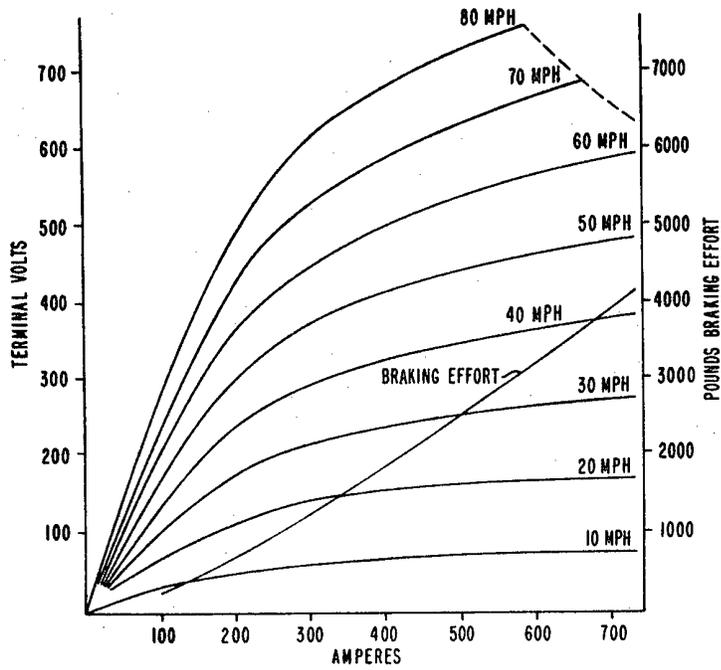


FIG. 19

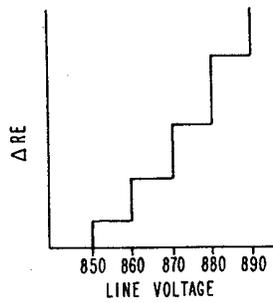


FIG. 20