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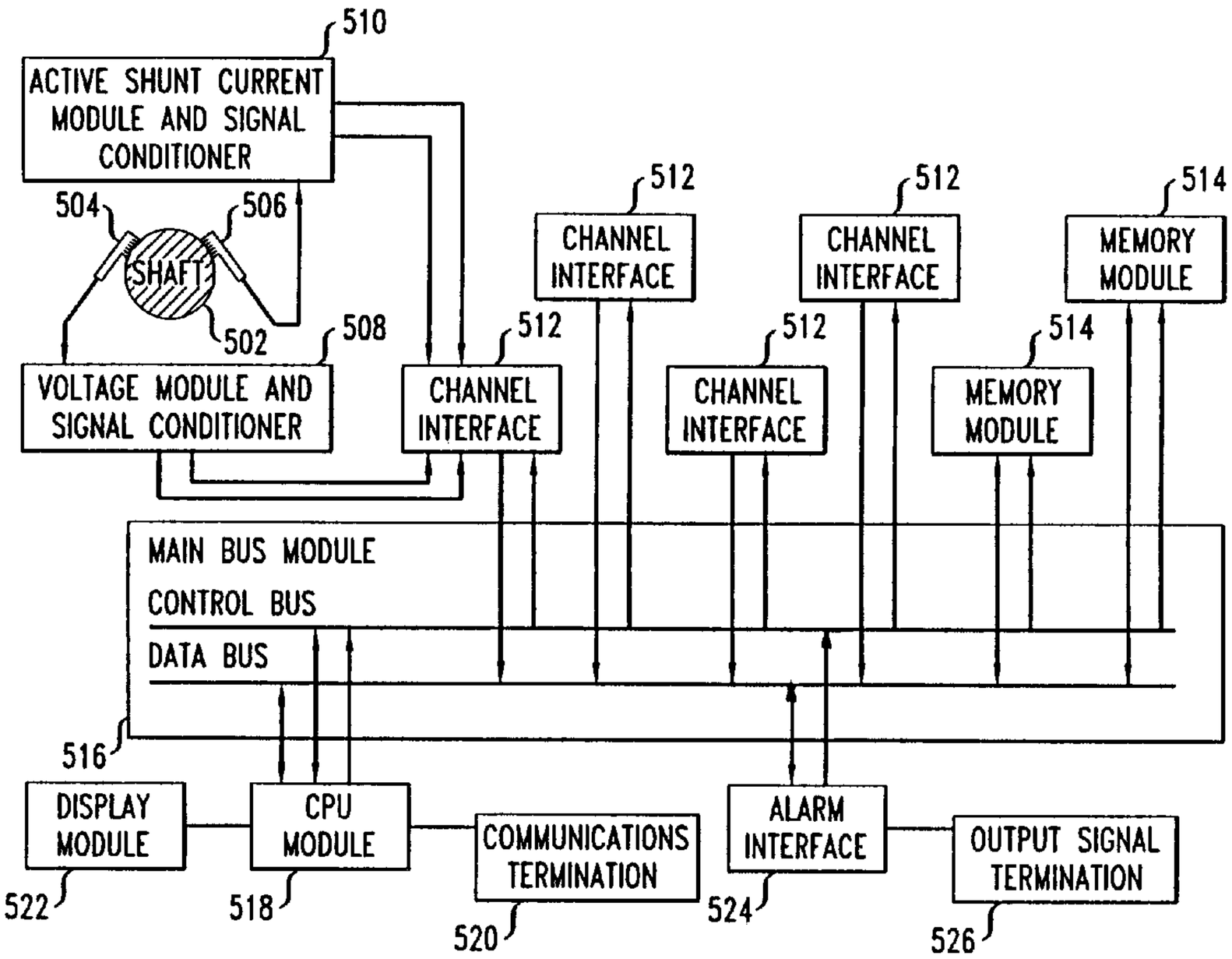
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(71) Demandeur/Applicant:
NIPPES, PAUL I., US

(72) Inventeur/Inventor:
NIPPES, PAUL I., US

(74) Agent: DEETH WILLIAMS WALL LLP

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(54) Title: SHAFT VOLTAGE AND CURRENT MONITORING SYSTEM



(57) Abrégé/Abstract:
A rotating machinery monitor provides a warning that is indicative of a developing problem with the rotating machinery (502). The rotating machinery monitor has at least one current sensor (510) for detecting shaft grounding current in the rotating machinery, at least one voltage sensor (508) for detecting shaft voltage in the rotating machinery (502), a change detector (602) for determining rate of change in the shaft grounding current and a change detector (604) for determining rate of change in the shaft voltage, and an evaluation system (518) for producing a warning (526) as a function of the change in the shaft grounding current, the rate of change in the shaft voltage, the shaft grounding current and the shaft voltage.

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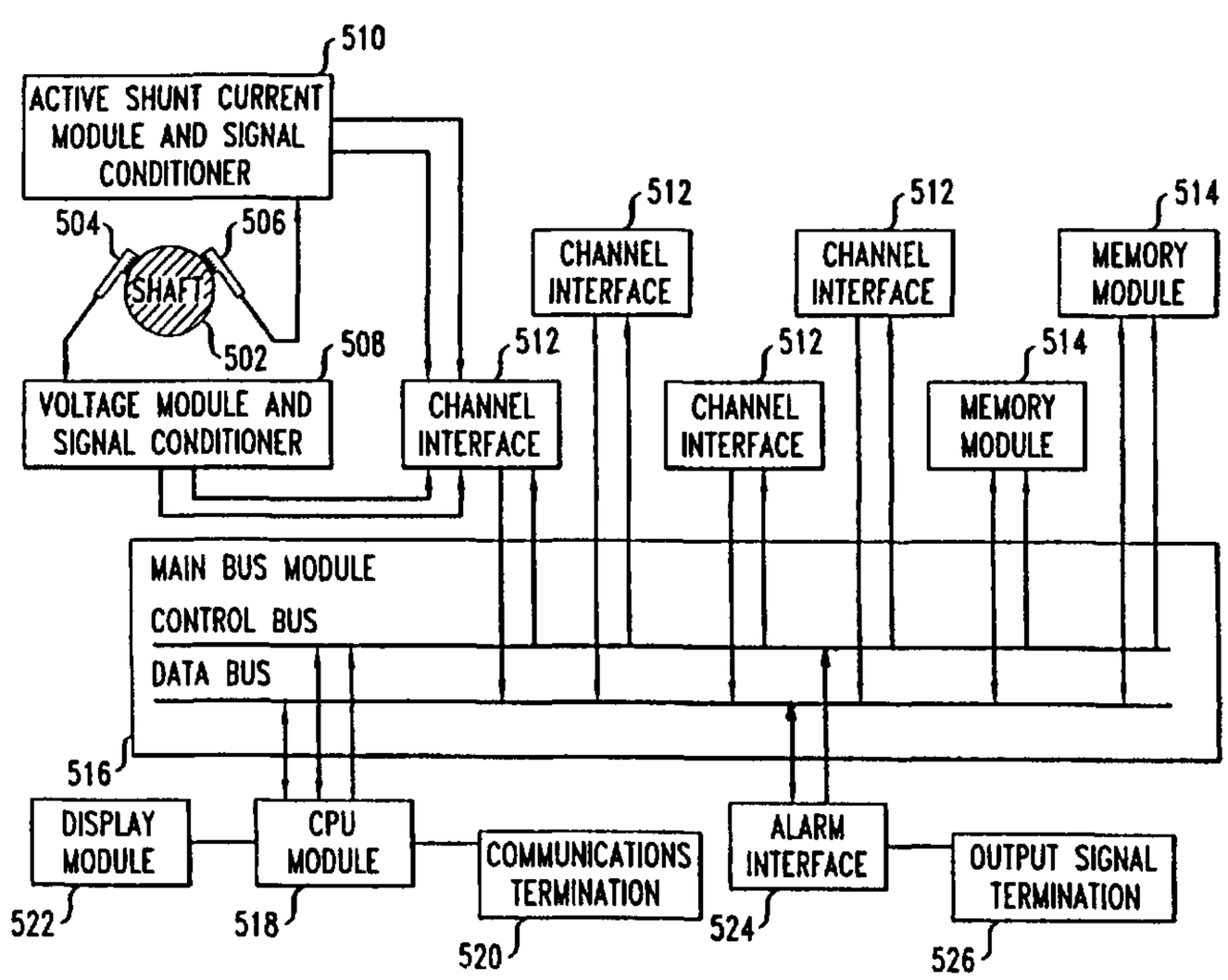
(71)(72) Applicant and Inventor: NIPPES, Paul, I. [US/US]; 1 Tall Tree Road, Middletown, NJ 07748 (US).

(74) Agent: KRIVOSHIK, David, P.; Mathews, Collins, Shepherd & Gould, Suite 306, 100 Thanet Circle, Princeton, NJ 08540 (US).

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(54) Title: SHAFT VOLTAGE AND CURRENT MONITORING SYSTEM



(57) Abstract

A rotating machinery monitor provides a warning that is indicative of a developing problem with the rotating machinery (502). The rotating machinery monitor has at least one current sensor (510) for detecting shaft grounding current in the rotating machinery, at least one voltage sensor (508) for detecting shaft voltage in the rotating machinery (502), a change detector (602) for determining rate of change in the shaft grounding current and a change detector (604) for determining rate of change in the shaft voltage, and an evaluation system (518) for producing a warning (526) as a function of the change in the shaft grounding current, the rate of change in the shaft voltage, the shaft grounding current and the shaft voltage.

Shaft Voltage and Current Monitoring System

FIELD OF THE INVENTION

This invention relates to rotating machinery and more particularly to a shaft sensor for monitoring rotating machinery.

BACKGROUND OF THE INVENTION

Monitoring and maintenance methods for rotating machinery, such as generators, motors and turbo-machinery, currently lack sufficiently reliable for accurately indicating certain important problems, such as cracking of power transmission components or their structural support members, inadequacy of local lubrication, excessive wear, shorted insulation, stator winding faults, and various other failures. Rotating machinery faults and failures lead to unnecessary expenses, which could be avoided by timely repair or scheduled maintenance. The occasional catastrophic failure of rotating machinery can result in costly repairs and system down-time, having a rippling effect on businesses dependent on the plant machinery or the power generated by the plant machinery. Downtime caused by a failure of rotating machinery reduces productivity and profitability.

Therefore, there is a need to monitor rotating machinery to reliably predict development of a failure as well as to determine when the rotating machinery operation is normal.

SUMMARY OF THE INVENTION

The present invention is a rotating machinery monitor, which provides a warning that is indicative of a developing problem with the rotating machinery. The rotating machinery monitor has at least one current sensor for detecting shaft grounding current in the rotating machinery, at least one voltage sensor for detecting shaft voltage in the rotating machinery, a change detector for determining rate of change in the shaft grounding current and a change detector for determining rate of change in the shaft voltage, and an evaluation system for producing a warning as a function of the change in the shaft grounding current, the rate of change in the shaft voltage, the shaft grounding current and the shaft voltage.

DESCRIPTION OF THE DRAWINGS

The present invention is described in detail below in conjunction with the drawings, of which:

FIG. 1 shows a typical wave form produced from the signals of the shaft-riding brushes;

FIG. 2a, 2b and 2c show traces of the shaft voltage/current signals for analysis and/or recording;

FIG. 3 is an exemplary schematic representation of the present invention VCM in use with a large turbine generator;

FIG. 4 is an exemplary schematic representation of the present invention VCM in use with industrial-class machinery;

FIG. 5 shows a schematic block diagram of a representative embodiment of the present invention;

FIG. 6 shows a more detailed schematic block diagram of the channel interface; and,

FIG. 7 shows a more detailed schematic block diagram of a CPU module.

DETAILED DESCRIPTION

In rotating machinery a shaft imbalance, winding deficiency, seal failure, bearing failure and other similar failures result in changes to a normal shaft voltage/current, which can be sensed using a pick-up on the rotating shaft. The present invention, shaft voltage current monitoring system for early warning and problem detection, is a monitoring system which tracks shaft voltages and currents, providing advance notification of most unit problems. The monitoring system employs a shaft voltage/current monitor (the VCM), which provides an indication of the start of a problem in rotating machinery. However, the shaft voltage/current signals require a specially trained observer and an intimate knowledge of system failure profiles to make sense out of the raw signals.

Trending of VCM signals over time indicates development of specific irregularities when they first occur, long before standard instruments and monitors respond to the abnormality. Traditional instruments and monitors

indicate and/or alarm only after an abnormality has existed for sufficient time to generate enough heat, vibration, noise or contamination to be indicated or to set off an alarm, by which time, damage has already occurred. An advance warning is provided by the VCM system, either indicating a definite problem requiring action, or alerting operators that they should note trends of conventional instruments and monitors for potential development of a problem. Corrective measures, can then be implemented as the situation dictates, typically before damage occurs. Further, a prediction can be made as to the future of shaft voltage and current monitoring in rotating machinery, thus enabling the VCM system to act as a precursor and confirming factor in unit operation and maintenance.

The VCM system, using the shaft as a sensor provides shaft signals, which alert the operators and engineers to take either definite action or to exercise precautions. Such precautions can include the monitoring and trending of conventional sensors and instruments in order to identify and possibly confirm an indicated condition.

One representative embodiment of the VCM system utilizes surface mount technology in the design of the circuit board, thus providing a relatively small, yet highly functional system which can be integrated into the machine/motor. As the VCM system is typically mounted near the machine, it is considered a "smart field sensor." The VCM system input consists of current and voltage signals from insulated shaft riding brushes employed to ground the

shaft and sense shaft voltages. While the VCM system can be fed from any type of insulated shaft riding brush, a high quality brush is preferable because of its very reliable performance. Two different shaft-riding brushes include the reliable bristle type and a copper strap used as a brush. With frequent maintenance, the strap has fairly good reliability, but it tends to fail if not cleaned often. The bristle brush picks up a real-time signal, depicting either current or voltage.

The VCM system utilizes real-time input of raw shaft quantities, grounding currents and shaft voltages. The signals are conditioned and converted for transmission to the signal processing and analysis system. The signals can equally well be converted into other standard forms for serial and parallel digital interfaces. The particular types of interfaces as well as conversion between the forms of signals are well known to those skilled in the art.

The shaft voltage and current input signals are processed such that the raw information is condensed by the VCM system, producing manageable data volume. A typical waveform, produced from the signals of the shaft-riding brushes is shown in FIG. 1 with the shaft signal plotted over time. This raw shaft signal is fed to a signal processing and analysis system. A normalized and condensed signal, representative of the original wave, is available for signal evaluation and unit condition determination, either by a computer-based system, specialized digital circuit, analog circuit or hybrid system.

Referring to FIGs. 2a, 2b and 2c there are shown traces of the VCM signals which are supplied for analysis. Note that in one embodiment, a representative 5 ms interval on the real-time trace is comparable to one hour on the VCM output traces, constituting a reduction in data by 720,000 times. Other levels of data reduction are equally well suited, dependent upon the devices interfaced and how the analysis is performed.

FIG. 2a shows variations in the shaft voltage and grounding current, indicating the unit is "OK." FIG. 2b shows correspondence of the other traces, except for one period where the voltage drops and the current increases slightly, arousing suspicion of possible problem development. FIG. 2c shows wild deflections, a significant deviation from the straight-line low-level characteristics it had for days before and after this period. The cause for this behavior is still not known; however, it is indicative of a developing problem. Problems producing this type of characteristic include stator core lamination packet shorting, rotor field winding turn shorting, or stator coil transposition shorting. All of these problems will appear stable after the faulting components melt together, thereby stressing the importance of continuous monitoring so as not to miss an event. None of this damage is shown on conventional instrumentation during early stages of its development.

Since the shaft grounding current and voltage are very sensitive to changes in the machinery, a developing problem can be detected long before there is damage and long before these are indicated by conventional monitors

and/or unit instrumentation. An example of this is the occurrence of a shaft rub. The instant a metal-to-metal rub exists, the VCM system will detect an increase in the shaft grounding current and a decrease in the shaft voltage, while vibration and temperature sensors will not show indications of an abnormality until after the rub has existed long enough for damage to occur which produces excessive heat and vibration. It should be noted that the VCM system warnings can be used in combination with temperature, vibration and other instruments.

Interpretation of the VCM output signals is highly dependent on the location of the train grounding brushes and voltage sensing brushes. On larger trains, such as turbine generators, dual VCM's are used, one for each brush or group of brushes. Multiple brushes and VCM's carry higher grounding currents and provide redundancy, which is useful for ensuring continuous shaft grounding during brush maintenance.

FIG. 3 shows one example of applying first grounding brush 302, second grounding brushes 304, first shaft voltage sensing brush 306 and second shaft voltage sensing brush 308 to a large turbine generator 300. The large turbine generator 300 is essentially a turbine 316 coupled to a generator 314. The turbine 316 is typically comprised of a HP turbine 318, which is coupled to an IP turbine 320, which is coupled to an LP turbine 322. Note that the grounding brush cables connect to current shunts or tapped resistors 310 if current limiting is desired. From here, the grounding cables connect to the nearby lower bearing housing 312, shown at the generator 314. The turbine bearing may alternatively

be selected where there is voltage between the generator frame and ground. In any case, the lower bearing housing, along with the generator frame and turbine casings should be bonded to the station ground grid. A first VCM 328 and a second VCM 330 are coupled to first and second grounding brushes 302 and 304, first and second shaft voltage sensing brushes 306 and 308, and current shunt or tapped resistors 310. The first VCM 328 and the second VCM 330 provide data signals and alarm signals 332 which are coupled to a signal processing analysis system 324. The signal processing analysis system 324 can be a dedicated circuit, digital logic circuitry, a programmable circuit, a time shared or time sliced device, a digital processor, a microprocessor, as well as similar devices. This circuitry can be made up of solid-state comparators, displays, converters, transmitters and conditioners, providing notification of possible developing problems. A voltage spike and transient absorber 326 can be optionally coupled to the second shaft voltage sensing brush 308 as needed.

Additional shaft grounding may be needed at the collector ring, or exciter end of the generator, due to possible high-frequency voltages imposed by solid state circuits, as in exciters. These high frequencies are known to damage bearings even when they are insulated, because the insulation acts as a capacitor, passing high frequency currents through the insulation. This current is easily shunted to ground through a tuned filter 316 attached to the second voltage sensing brush 308. An additional and important role of the second sensing

brush 308 is to detect loss of insulation integrity at the outboard bearing, hydrogen seal, or coupling.

The first sensing brush 306, located at the turbine 316, detects an increase in static charge in the turbine 316. Both the first sensing brush 306 and the second sensing brush 308 signal first development of rubs as a sudden drop in voltage, usually to ½ the prior value. Additional indications include: a high voltage at the first sensing brush 306, inversely proportional to steam temperature indicates wet steam in the turbine 316; high current in the grounding brushes 302 and 304 and low voltage at the second sensing brush 308 indicates loss of bearing or seal insulation; rapid escalation in both the voltage of the second sensing brush 308 and grounding currents indicates a developing stator winding fault; erratic and pulsing voltage and current indicates stator lamination shorting and melting; long term gradual increases in voltage and current indicate a shift in the air gap; pulsing followed by a gradual increase in shaft voltage and current indicates rotor winding faulting; shaft voltage changes related to excitation changes may indicate the need for a shaft voltage harmonic filter; low brush current indicating brush or grounding maintenance required.

Referring to FIG. 4, there is shown an exemplary embodiment of the application of the VCM system to industrial-class machinery 402, such as boiler feed pumps, fans and turbo-compressor trains. Sensing brush 404 is coupled between the shaft at the outboard end of the machinery 402 and the VCM 406. A grounding brush 408 is coupled to the shaft at the inboard end of the

machinery 402. The grounding brush 408 is coupled to the VCM 406 through a current shunt 410 and is coupled directly to the VCM 406. The current shunt 410 is coupled to the bearing housing 412. The VCM 406 provides data signals and alarm signals 414, which are coupled to a signal processing analysis system 416.

Referring to FIG. 5 in conjunction with FIGs. 6 and 7 there is shown a block diagram of one embodiment of the present invention. Although the present invention is well suited for implementation by board level integration, it is equally well suited for higher integration, including hybrid analog/digital boards, application specific integrated circuits (ASIC) and hybrid analog/digital integrated circuits. The higher level of integration provides the ability to increase reliability of motors in mission critical applications such as medical devices, aerospace industry and continuous process machinery.

In one embodiment, the motor can be designed as a replacement for existing motors, wherein an integral monitoring and alarm/warning are transparent to normal unit operation and further, the motor replacement with integral monitoring can be installed as a direct replacement for an existing motor. In another embodiment, where the motor replacement with integral monitoring is installed in equipment having digital communication capabilities, the reduced data and/or the alarm/warning information may be integrated through the digital communications.

Again referring to FIG. 5 there is shown a shaft 502 in cross section having shaft sensors 504 and 506. Shaft sensor 504 is coupled to voltage module and signal conditioner 508. Shaft sensor 506 is coupled to active shunt current module and signal conditioner 510. Channel interface 512 is typically one of four, which are utilized in this embodiment. The channel interface 512 may be a plug in module/board, or integrated as an ASIC. A first and second output of the active shunt current module and signal conditioner 510 are coupled to the channel interface 512. A first and second output of the voltage module and signal conditioner 508 are coupled to the channel interface 512.

The outputs of the channel interface 512 are coupled to a main bus module 516. A control bus of the main bus module 516 is coupled to each channel interface 512, memory modules 514 and alarm interface 524. A data bus of the main bus module 516 is coupled to each channel interface 512, memory modules 514 and alarm interface 524. The alarm interface 524 is coupled to an output signal termination block 526 by a 4-20 mA or other suitable interface.

A CPU module 518 is coupled to the control bus and the data bus of the main bus module 516. The CPU module 518 also coupled to a communications interface 520 and a display module 522. The CPU module 518 with suitable program memory contains the diagnostic algorithm.

Again referring to FIG. 6 there is shown shows a more detailed schematic block diagram of the channel interface 512. A first output of the

active shunt current module and signal conditioner 510 is coupled to first low pass filter 602. A first output of the voltage module and signal conditioner 508 is coupled to second low pass filter 604. A second output of the active shunt current module and signal conditioner 510 and a second output of the voltage module and signal conditioner 508 are coupled to current/voltage selection jumpers 606. The output of the first low pass filter 602 is coupled to peak current circuitry 608 and average current circuitry 610. The output of second low pass filter 604 is coupled to peak voltage circuitry 612. The outputs of peak current circuitry 608, average current circuitry 610 and peak voltage circuitry 612 are coupled to function selection jumpers 614. The output of the function selection jumpers 614 is coupled to an analog to digital converter 616. The output of the analog to digital converter 616 is coupled to a first eight-bit latch 620 and to the least significant bits of a second eight-bit latch 622. Card type select jumpers 624 are coupled to V+ and the most significant bits of the second eight-bit latch 622. The output of the current/voltage selection jumpers 606 is coupled to analog to digital encoder and latch 618. The current/voltage selection jumpers 606, the function selection jumpers 614 and the card type select jumpers 624 can be implemented with any number of suitable methods or devices including switches and with circuitry and the description should not be considered limiting. The outputs of the first eight bit latch 620, the second eight bit latch 622, and the analog to digital encoder and latch 618 are coupled to a data bus of main bus module 516.

Again referring to FIG. 7 there is shown shows a more detailed schematic block diagram of the CPU module 518. The CPU module 518 is coupled to the main bus module 516. The CPU module 518 contains a card/device select 704, which is coupled to the control bus of the main bus module 516. The control bus and the data bus of the main bus module 516 are coupled to a digital microcontroller with suitable program memory (such as a flash EEPROM) 702, which is coupled to a serial communications interface 520, graphics display controller 708, and external memory 706. The external memory 706 and the graphics display controller 708 are coupled through a data bus to the card/device select 704. The graphics display controller 708 is coupled to a suitable display module 522 such as a LCD graphics display module. The digital microcontroller 702 with suitable program memory contains the diagnostic algorithms.

The detailed design, of the many implementations of the functional circuit elements described herein, are well known to those skilled in the art. Many other embodiments of the functional elements are equally well suited. While the present invention VCM is ideally suited for use in a digital environment and has been so described, the fundamental concepts are applicable to an analog environment as well. The actual signals being monitored may be digitized at a number of stages, or may remain in analog form and be compared to predetermined levels for detection and prediction of problems.

Indications of problems includes: voltage decrease to half or less and current significant increases indicates shaft rub; and current and voltage increases by two times indicates static charge from steam, oil or product flow. Where the monitored equipment is an electrical machine, indications of problems includes: current increase and voltage decrease indicates loss of bearing, seal or coupling insulation; voltage and current 60 Hz erratic increase indicates developing stator core/winding faulting; high voltage and current at 60 Hz indicates magnetic circuit asymmetry or air gap misalignment; and pulsing then gradually increasing 60 Hz voltage and current indicates rotor winding faulting. Additional brushes and VCM's may be required on some trains because they include electrically active items, such as motors and generators. This is also the case where there are electrically separate shafts needing protection, such as on the opposite side of gears and couplings, if insulated or gear-type. The need should be determined by the designer and the user, and should be based on the particular characteristics of the machinery.

With predictive information being available from the VCM system, one way to improve performance and on-line operating time is to programmatically set up algorithms to automatically recognize and diagnose possible development of a problem. The algorithms can be based upon the conditions described below in Tables 1, 2, 3 and 4. Shaft voltage and grounding current monitoring by the VCM system is analyzed to determine unit condition and provide predictive capabilities. Some representative examples of this analysis follows.

Shorted insulation or lack of insulation on electrical machinery outboard bearings and, where applicable, couplings is indicated by low voltage on the voltage sensing brush at the motor outboard end, accompanied by very high current in the inboard end grounding brush.

Shaft rubs are indicated, during testing, when a motor exhibited a drop in shaft voltage to ½ its previous value. It should also be noted that an oscilloscope trace of this voltage had the appearance of a half-wave rectifier, rather than the prior full wave trace. Disassembly of the motor revealed that a rub had developed. When cleared, the full wave character of the shaft voltage was restored.

Electrostatic charge generation was indicated for a 750 MW turbine generator which had a shaft grounding current of 3.0 peak amperes on the VCM and a steam inlet to the turbine temperature of 970°F. When this temperature was dropped to 950°F, the grounding current increased to 6.0 amperes. Thus indicating that wet steam, a known factor in electrostatic voltage generation, was the probable cause. When electrostatic shaft voltage generation is due to dry steam where it enters turbines with partial circumference entry ports or openings, voltages in the hundreds of volts have been measured.

Harmonics and voltage spikes, in the shaft, are found to reach hundreds of volts unless reduced by shaft grounding or reliable harmonic suppresser circuits in the excitation supply.

The VCM circuitry alarming on current below the minimum setting indicates loss of shaft grounding.

High, and possibly increasing, residual magnetism may be the cause of high and/or increasing shaft voltage and grounding currents, a condition requiring degaussing as dictated by the seriousness of the voltage condition or damage to bearings.

Electrical machinery defects include stator winding faults, core lamination shorting, broken rotor bars in induction machines, shorted turns in synchronous machinery fields, stator gap or segment misalignment, and power system-induced unbalances or harmonics. All produce asymmetries in the magnetic or electric circuits, resulting in increases or changes in the shaft voltage and grounding currents.

The current shunts in the shaft grounding brush cable and voltage sensing brushes provide raw signals to the VCM system for processing. By processing and conditioning the sensed signals they are analyzed and evaluated to provide warning of developing problems with the rotating machinery. Table 1 presents the warning criteria for electrical electrically isolated rotating machinery shafts. Table 2 presents the warning criteria for induction motors and induction generators. Table 3 presents the warning criteria for synchronous motors and synchronous generators. Table 4 presents the warning criteria for direct current motors and direct current generators. The particular warning criteria is indicative of the developing problems, which are identified at the top

of each corresponding column. Appended to the end of each table is information which can be obtained from some types of conventional instruments and monitors for trending and either confirming, or not confirming, the indicated problem development. Optionally, the information from the conventional instrument and monitor trending can be incorporated into the signal processing and analysis, enhancing the value of the warning. Table 5 contains a summary of legends and notes, which are useful in understanding Tables 1, 2, 3 and 4.

Table 1

ITEM	1 Shaft Grounding Maintenance	2 High Electrostatic Charge on Shaft	3 High Residual Magnetism	4 High Localized Internal Residual Magnetism	5 Shaft element Contact to Stationary element (Bearing, Seal)
Ipk	<<Ipkmn	>Ipkmx	>Ipkmx	<Ipkmn	>>Ipkmx↑it
Iav	<<Iavmn			<Iavmn	>>Iavmx↑it
f	er	er	nrf		nrf
Vpk	↑it		<Vpkmx	<Vpkmn	↓it
Ipk/Iav		>2.	<2.	.	<2.
EM/ f		?/ er	↑/ nrf	↑/ nrf	↑/ rf

	Based upon changes in value and with time of machine or train conventional instruments				
Brg. Vibr.		↑ot	↑ot	↑ot	↑st
Brg.Temp.		↑ot	↑ot	↑ot	↑st
Oil Particles.			↑ot	↑ot	
Audible			↑ot	↑ot	↑st
Shaft displacement		↑ot	↑ot	↑ot	

CONFIRM #2; Ipk=0	VCM voltage readings with shaft grounding disconnected. Current flow in brgs, etc.?				
Vpk	<Vpkmn	>>Vpkmx	>Vpkmx	<Vpkmn	>Vpkmx
Vav	<Vavmn	<Vavmx.	>Vavmx	<Vavmn	>Vavmx
Vf		er	nrf		nrf
Vpk/Av		>2.			
Visual & Test	Inspect and ohmeter test brush, cables & grounding circuit	Frosting on Bearings, seals	Heavy frosting, spark tracks at bearings. Shaft drops and/or moves axially	Dismantle and make magnetic survey of internal components	Rub t of rotating to stationary parts. Thermal distortion, discoloration
Causes	a. There is no stray voltage source. b. Brush contact to the shaft is lost. c. Brush grounding circuit is open.	a. Wet Steam. b. Dry steam. c. High oil velocity. d. Oil filter.	a. Magnetized components, rotor or stator. b. Improper welding practices. c. Electric currents. d. Magnetic Particle inspection. e. Lightning.	a. Magnetism inside unit, not measurable either as magnetism or generated voltage external to the unit. b. Usually a rub, installed magnetized part, welding, MPI etc.	a. Looseness, movement. b. Imbalance. c. Foreign objects. d. Mechanical distortion.

Table 2

ITEM	A Shorted insulation on bearing, seal or coupling.	B Shorted stator or rotor core laminations.	C Armature winding turn or transposition fault.	D Low level armature winding fault to ground.	E Electrical system has phase unbalance or harmonics.	F Uneven Air gap or stator segment misalignment	G Induction motor bar or end ring breakage or discontinuity.
Ipk	>>Ipkmx↑st	>Ipkmxer	>Ipkmx↑ot	>Ipkmx↑ot	>Ipkmx	>Ipkmx	>Ipkmx
Iav	>>Iavmx↑st	>Iavmxer	>Iavmx↑ot	>Iavmx↑ot	>Iavmx	>Iavmx	>Iavmx
f	ef	nef	nef	ef+3h	nef	nrf	nrf
Vpk	<Vpkmnit	>Vpkmxster	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx
Ipk/Iav	<2.	<2.	<2.	<2.	<2.		

CONFIRM 1	Based upon changes in value and with time of machine or train conventional instruments						
Brg. Vibr.	↑st					↑ot	↑st
Brg.Temp.	↑st						
Arm. Temp.		↑ot	↑st				
OilParticles	↑st						
Audible		↑ot			↑ot		↑ot
Core Vibr.		↑ot			↑ot	↑ot	
Harm Iph		↑iter	↑ot	↑ot	↑ot		↑ot+sbf
Harm Vph			↑ot				
Par. Disch.		↑it	↑it	↑ot			
Gas Monitor		↑ster	↑ot	↑ot			

CONFIRM #2	Based on VCM voltage readings when grounding brush(es) are disconnected momentarily						
Vpk	>Vpkmn	>Vpkmxer	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx
Vav	>Vavmn	>Vavmxer	>Vavmx	>Vlavmx	>Vavmx	>Vavmx	>Vavmx
Vf	ef	nef	nef	ef+3h	nef	nrf	nrf
Visual and Tests	Look for shorted insulation; measure insulation resistance with ohmmeter following procedure in IEEE #112	** Inspect lamination edges with a 60x microscope. Perform core "loop test" and possibly el-cid test	** Inspect coils for signs of over heating. Measure phase, coil group resistances, progressively to isolate.	** Megger, high-pot test armature phases then coil groups and coils to isolate fault	Operating examination and fast fourier analysis on the power system voltages and line currents	** Look for possible weld cracks, core or segment shifts. Measure air gap fully around the bore, both ends.	** Confirm side band test results by careful rotor cage inspection, broken bar test and x-ray examinations.
Causes	Foreign object, bad design or assembly	Foreign object, loose, tight, or overheated core.	Short circuit between coil Adjacent turns or conductors.	Coil fault near neutral or start of a large fault. to ground.	Unbalance or harmonics of the electrical power system	Misalign rotor in stator, broken welds, no dowels	Inertia, load too high for starting inertia or poor braze

Table 3

ITEM	A Shorted insulation on bearing, seal or coupling.	B Shorted stator core laminations.	C Armature winding turn or transposition fault.	D Low level armature winding fault to ground.	E Electrical system has phase unbalance or harmonics.	F Uneven Air gap or stator segment misalignment	H Short circuiting of field excitation winding turns	I Field excitation winding ground fault	J voltage or current transients from excitation current.
Ipk	>Ipkmx↑st	>Ipkmxer	>Ipkmx↑ot	>Ipkmx↑ot	>Ipkmx	>Ipkmx	>Ipkmx↑er	>>Ipkmxit	>>Ipkmx
Iav	>Iavmx↑st	>Iavmxer	>Iavmx↑ot	>Iavmx↑ot	>Iavmx	>Iavmx	>Iavmax↑er	>>Iavmsit	<Iavmn
f	ef	nef	nef	ef+3h	nef	nrf	nxrf	nef	nef
Vpk	<Vpkmnit	>Vpkmxer	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx↑er	>>Vpkmxit	>Vpkmx
Ipk/Iav	<2.	er	<2.	<2.			<2.		>2.

CONFIRM 1	Based upon changes in value and with time of machine or train conventional instruments								
Brg. Vibr.	↑st					↑ot	↑ot		
Brg.Temp.	↑st								
Arm. Temp.		↑ot	↑st						
OilParticles	↑st								
Audible		↑ot			↑ot				
Core Vibr.		↑ot			↑ot	↑ot			
Harm Iph		↑iter	↑ot	↑ot	↑ot				
Harm Vph			↑ot						
Par. Disch.		↑it	↑it	↑ot					
Gas Monitor		↑ster	↑ot	↑ot					
Fld grnd fault								↑it	

CONFIRM #2	VCM voltage readings with shaft grounding disconnected. Current flow in brgs, etc.?								
Vpk	>Vpkmn	>Vpkmxer	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>>Vpkmx
Vav	>Vavmn	>Vavmxer	>Vavmx	>Vlavmx	>Vavmx	>Vavmx	>Vavmx	>Vavmx	<Vavmn
Vf	ef	nef	nef	Nef+3h	nef	nrf	nrf		6xer
Visual and Tests	Look for shorted insulation; measure insulation resistance with ohmmeter following procedure in IEEE #112	** Inspect lamination edges with a 60x microscope. Perform core "loop test" and possibly el-cid test	** Inspect coils for signs of over heating. Measure phase, coil group resistances, progressively to isolate.	** Megger, high-pot test armature phases then coil groups and coils to isolate fault	Operating examination and fast fourier analysis on the power system voltages and line currents	** Look for possible weld cracks, core or segment shifts. Measure air gap fully around the bore, both ends.	High field current at load. Low rotor winding AC impedance turn test ** AC pole drop test. Dismantle rotor	*Low megger, Visual check collector, field leads. **To locate fault . May require removal and dismantle rotor	Oscilloscope trace of shaft voltage and current confirm excitation supply as the source.
Causes	Foreign object, bad design or assembly	Foreign object; loose, tight, or overheated core.	Short circuit between coil Adjacent turns or conductors.	Coil fault near neutral or start of a large fault. to ground.	Unbalance or harmonics of the electrical power system	Misalign rotor in stator, broken welds, no dowels	Rotor coil turn distortion due to centrifugal forces and thermal distortion	Weakness or breakdown of excitation winding, leads to ground	Excitation system transients with no suppression

Table 4

ITEM	A Shorted insulation on bearing, seal or coupling.	B Shorted armature core laminations.	C Armature winding turn fault.	D Low level armature winding fault to ground.	E-Commutator or brush problems causing circuit unbalance.	F Uneven Air gap or field pole misalignment.	H Short circuiting of field excitation winding turns	I Field excitation winding ground fault	J voltage transients from armature or excitationr supply .
Ipk	>Ipkmx↑st	>Ipkmxer	>Ipkmx↑ot	>Ipkmx↑ot	>>Ipkmxit	>Ipkmx	>Ipkmx↑er	>>Ipkmxit	>>Ipkmx
Iav	>Iavmx↑st	>Iavmxer	>Iavmx↑ot	>Iavmx↑ot	>>Iavmxit	>Iavmx	>Iavmax↑er	>>Iavmsit	<Iavmn
f	nrf	nrf	nrf	nrf	er	nrf	nrf	nrf	nef
Vpk	<Vpkmnit	>Vpkmxer	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx↑er	>>Vpkmxit	>Vpkmx
Ipk/Iav	<2.	er	<2.	<2.			<2.		>>2.

CONFIRM 1	Based upon changes in value and with time of machine or train conventional instruments								
Brg. Vibr.	↑st					↑ot	↑ot		
Brg.Temp.	↑st								
Arm. Temp.		↑ot	↑st						
OilParticles	↑st								
Audible		↑ot			↑ot				
Harm I		↑iter	↑ot	↑ot	↑ot				
Harm V			↑ot						
Fld grnd fault								↑it	

CONFIRM #2	VCM voltage readings with shaft grounding disconnected. Current flow in brgs, etc.?								
Vpk	>Vpkmn	>Vpkmxer	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>Vpkmx	>>Vpkmx
Vav	>Vavmn	>Vavmxer	>Vavmx	>Vlavmx	>Vavmx	>Vavmx	>Vavmx	>Vavmx	<Vavmn
Vf	nrf	nrf	nrf	nrf	er	nrf	nrf	nrf	nef
Visual and Tests	Look for shorted insulation; measure insulation resistance with ohmmeter following procedure in IEEE #113	** Inspect lamination edges with a 60x microscope. Perform core "loop test" and possibly el-cid test	** Inspect coils for signs of over heating. Measure phase, coil group resistances, progressively to isolate.	** Megger, high-pot test armature phases then coil groups and coils to isolate fault	Operating examination and fast fourier analysis on the power system voltages and line currents	** Look for possible weld cracks, core or segment shifts. Measure air gap fully around the bore, both ends.	High field current at load. Low rotor winding AC impedance turn test ** AC pole drop test. Dismantle rotor	*Low megger, Visual check collector, field leads. **To locate fault . May require removal and dismantle rotor	Oscilloscope trace of shaft voltage and current confirm excitation supply as the source.
Causes	Foreign object, bad design or assembly	Foreign object; loose, tight, or overheated core.	Short circuit between coil Adjacent turns or conductors.	Coil fault near neutral or start of a large fault. to ground.	Unbalance or harmonics of the electrical power system	Misalign rotor in stator, broken welds, no dowels	Rotor coil turn distortion due to centrifugal forces and thermal distortion	Weakness or breakdown of excitation winding, leads to ground	Excitation system transients with no suppression

Table 5

lpk is current peaks in the grounding brushes
lav is average current in the grounding brushes
Vpk is voltage peak of the voltage sensing brushes
Vav is voltage average of the voltage sensing brushes
mn is preset minimum value
mx is preset maximum value
nx represents "n" times the previous value or expected value
H represents higher than typical
f is Waveform Frequency
ef is electrical power frequency
rf is rotor frequency
sbf is current side band frequency
Inef is electrical power frequency plus harmonics
ef+3h is electrical power frequency plus its third harmonic
nrf is rotor frequency plus harmonics
ot represents over time
st represents in short time
it represents instantaneous
er represents erratic or pulsing behavior
EM is Electromagnetic pick-up signal on the operating unit, usually at the casing or bearing parting line.
< represents less than and << represents much less than
> represents more than and >> represents much more than
↑ represents increasing in value and ↓ represents decreasing in value

An analysis routine based on the warning criteria in Tables 1, 2, 3 and 4 is set to detect and indicate the earliest occurrence of possible machine and/or train problems. Problem development indications are most reliable when initial benchmark settings of measured variables are set for machines which are new or in good operating condition.

Numerous modifications and alternative embodiments of the invention will be apparent to those skilled in the art in view of the foregoing description. The signal conditioning and analysis circuitry can be implemented on a dedicated integrated circuit. The dedicated integrated circuit can be a

specialized analog device, a digital device, or a hybrid analog/digital device. Reduction of the conditioning and analysis circuits can enable the present invention, shaft voltage current monitoring system for early warning and problem detection, to be integrated into rotating machinery. The alarm/warning indicator may be integral and/or remote. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the best mode of carrying out the invention. Details of the structure may be varied substantially without departing from the spirit of the invention and the exclusive use of all modifications, which come within the scope of the appended claim, is reserved.

I CLAIM:

1. The invention as described and illustrated in the specification.

2. A rotating machinery monitor comprising:

at least one current sensor for detecting shaft grounding current in the rotating machinery;

at least one voltage sensor for detecting shaft voltage in the rotating machinery;

a change detector for determining rate of change in the shaft grounding current and a rate of change in the shaft voltage;

an evaluation system for producing a warning as a function of the change in the shaft grounding current, the rate of change in the shaft voltage and the average shaft grounding current;

wherein the warning is indicative of a developing problem with the rotating machinery.

3. The monitor as recited in claim 2 further comprising an electric motor wherein the at least one current sensor and the at least one voltage sensor are integral with the electric motor.

4. The monitor as recited in claim 2 or 3 wherein the change detector determines a first order derivative of the shaft voltage and a first order derivative of the shaft grounding current.

5. The monitor as recited in claim 2, 3 or 4 further comprising a sampling device for data reduction wherein real-time shaft current values and real-time shaft voltage values are compressed over time.

6. A method for monitoring rotating machinery comprising the steps of:

detecting shaft grounding current in the rotating machinery;

detecting shaft voltage in the rotating machinery;

determining rate of change in the shaft grounding current;

determining rate of change in the shaft voltage;

producing a warning as a function of the change in the shaft grounding current, the rate of change in the shaft voltage and the shaft grounding current, wherein the warning is indicative of a developing problem with the rotating machinery.

7. The method as recited in claim 6 wherein the step of determining rate of change in the shaft grounding current determines a first order derivative of the shaft grounding current.

8. The method as recited in claim 6 or 7 wherein the step of determining rate of change in the shaft voltage determines a first order derivative of the shaft voltage.

9. The method as recited in claim 6, 7 or 8 further comprising the step of sampling real-time shaft current values and real-time shaft voltage values over time.

10. The invention as recited in claim 2, 3, 4, 5, 6, 7, 8 or 9 wherein the warning is further a function of waveform frequency.

11. The invention as recited in claim 2, 3, 4, 5, 6, 7, 8, 9 or 10 wherein the warning is further a function of rotor frequency

12. The invention as recited in claim 2, 3, 4, 5, 6, 7, 8, 9 10 or 11 wherein the warning is further a function of the ratio of peak grounding current to average grounding current.

13. The invention recited in claim 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 or 12 wherein the function is defined by table 1 or table 2 or table 3 or table 4.

FIG. 1

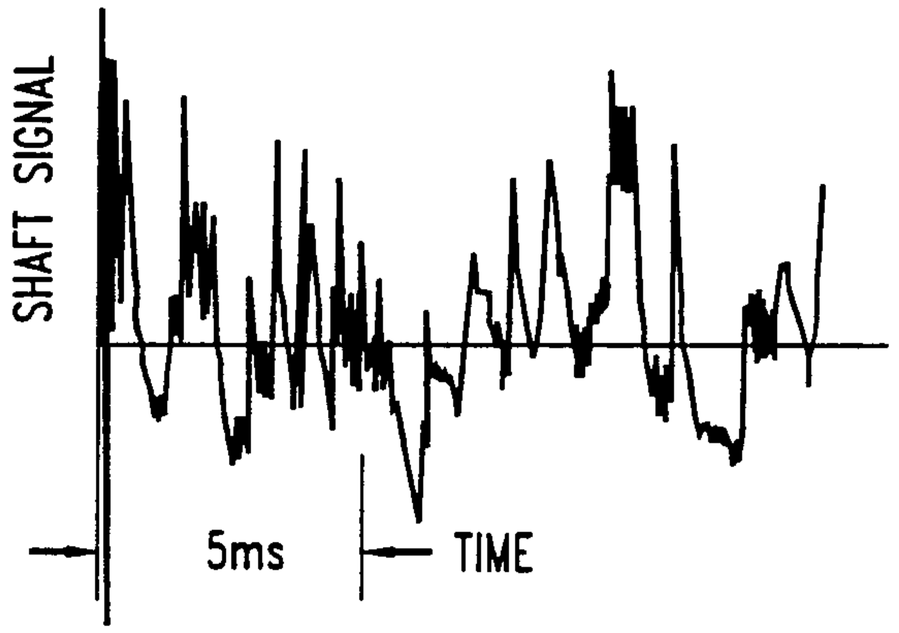


FIG. 2A

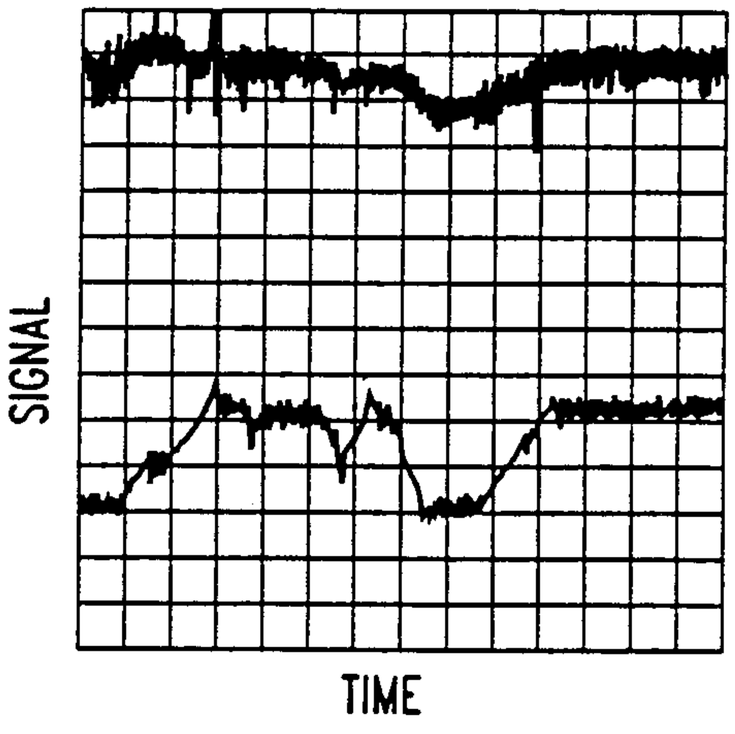


FIG. 2B

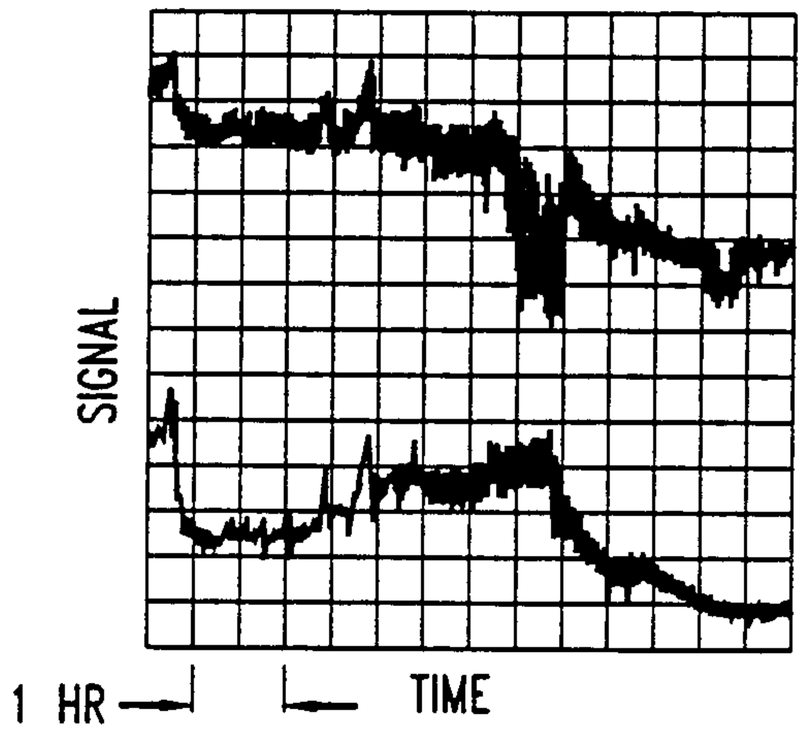
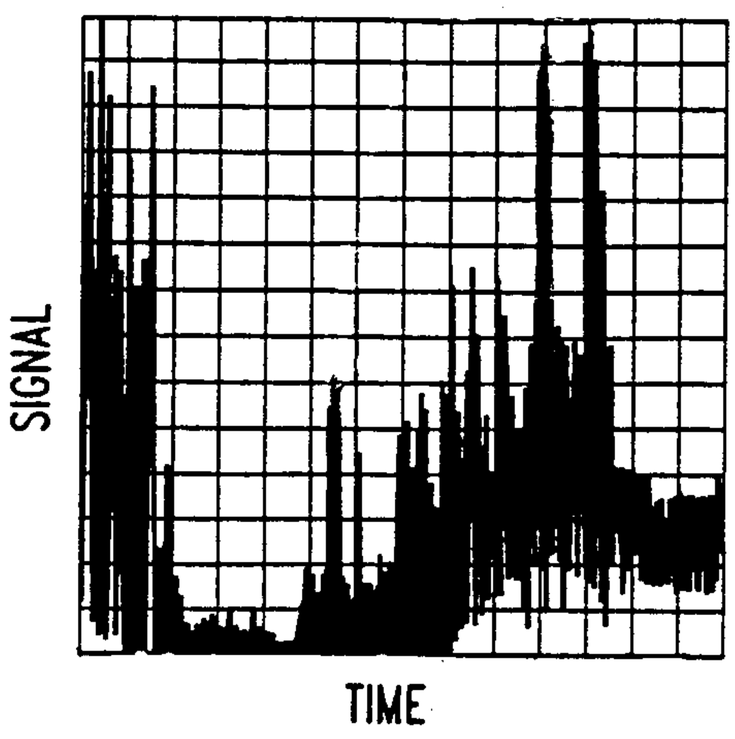


FIG. 2C



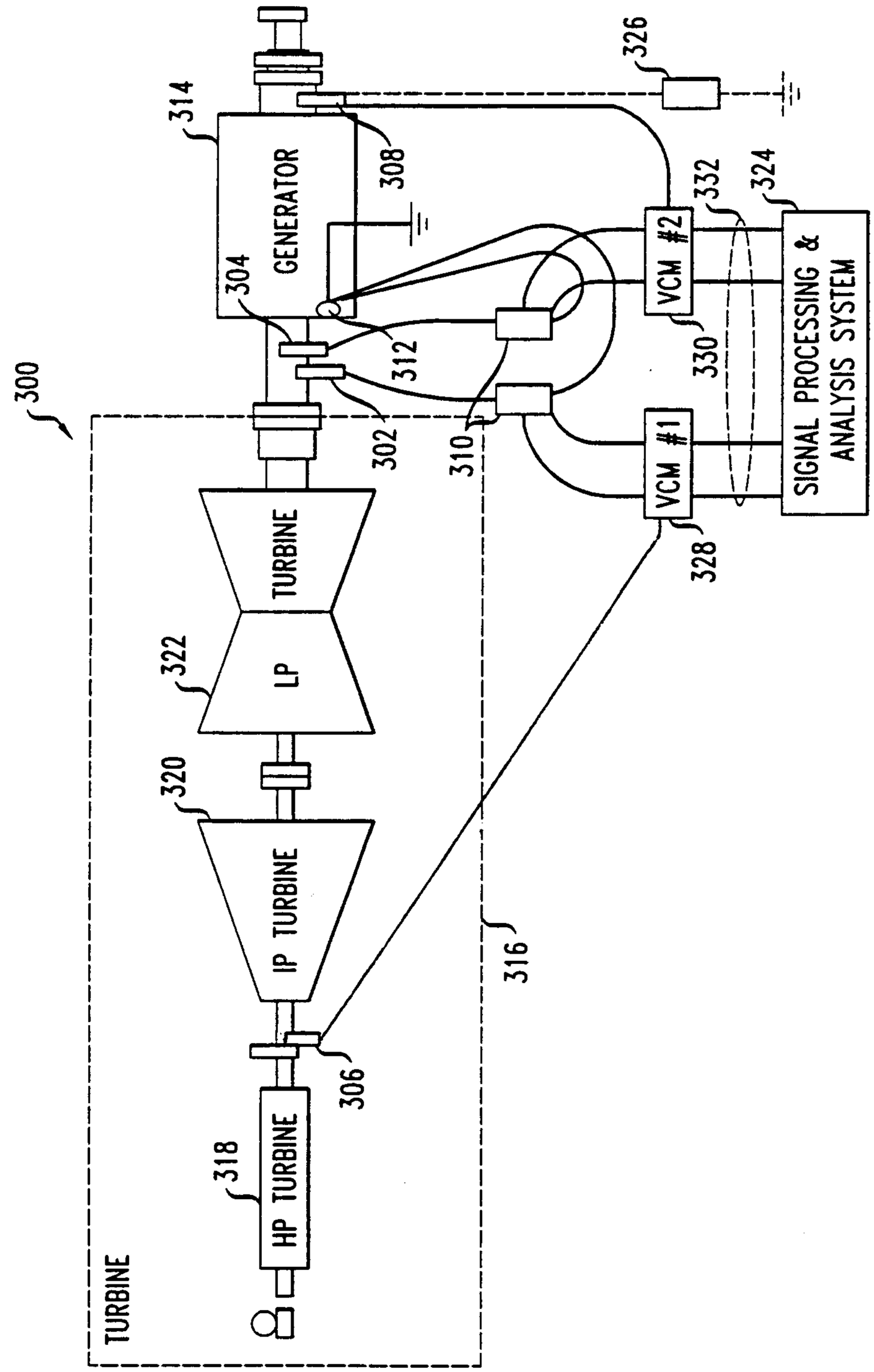

300
314
GENERATOR
304
308
326
312
302
310
TURBINE
LP
322
320
IP TURBINE
318
HP TURBINE
306
316
VCM #2
VCM #1
332
330
328
324
SIGNAL PROCESSING & ANALYSIS SYSTEM

FIG. 3

FIG. 4

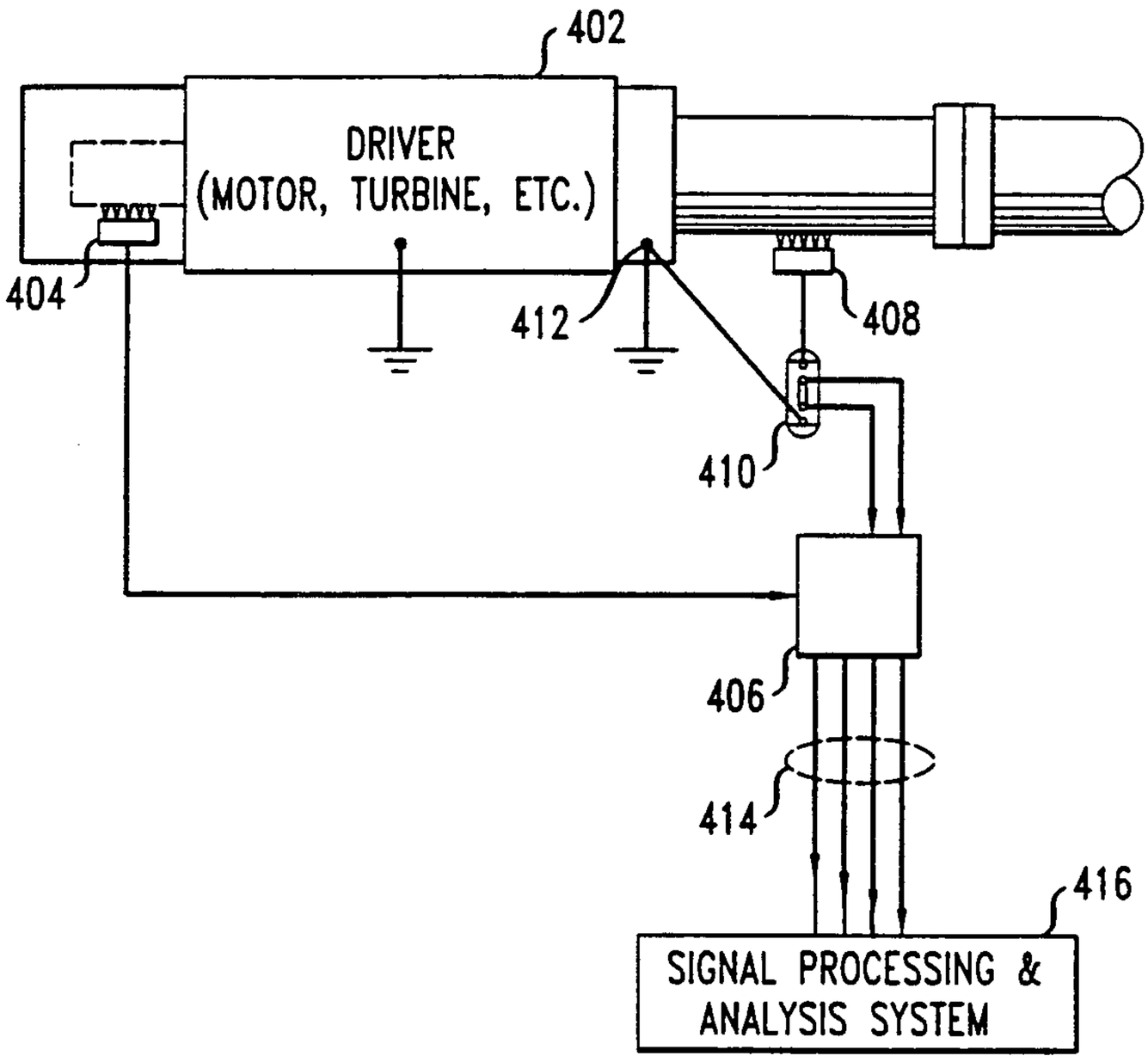

402
DRIVER
(MOTOR, TURBINE, ETC.)
404
412
408
410
406
414
416
SIGNAL PROCESSING &
ANALYSIS SYSTEM

FIG. 5

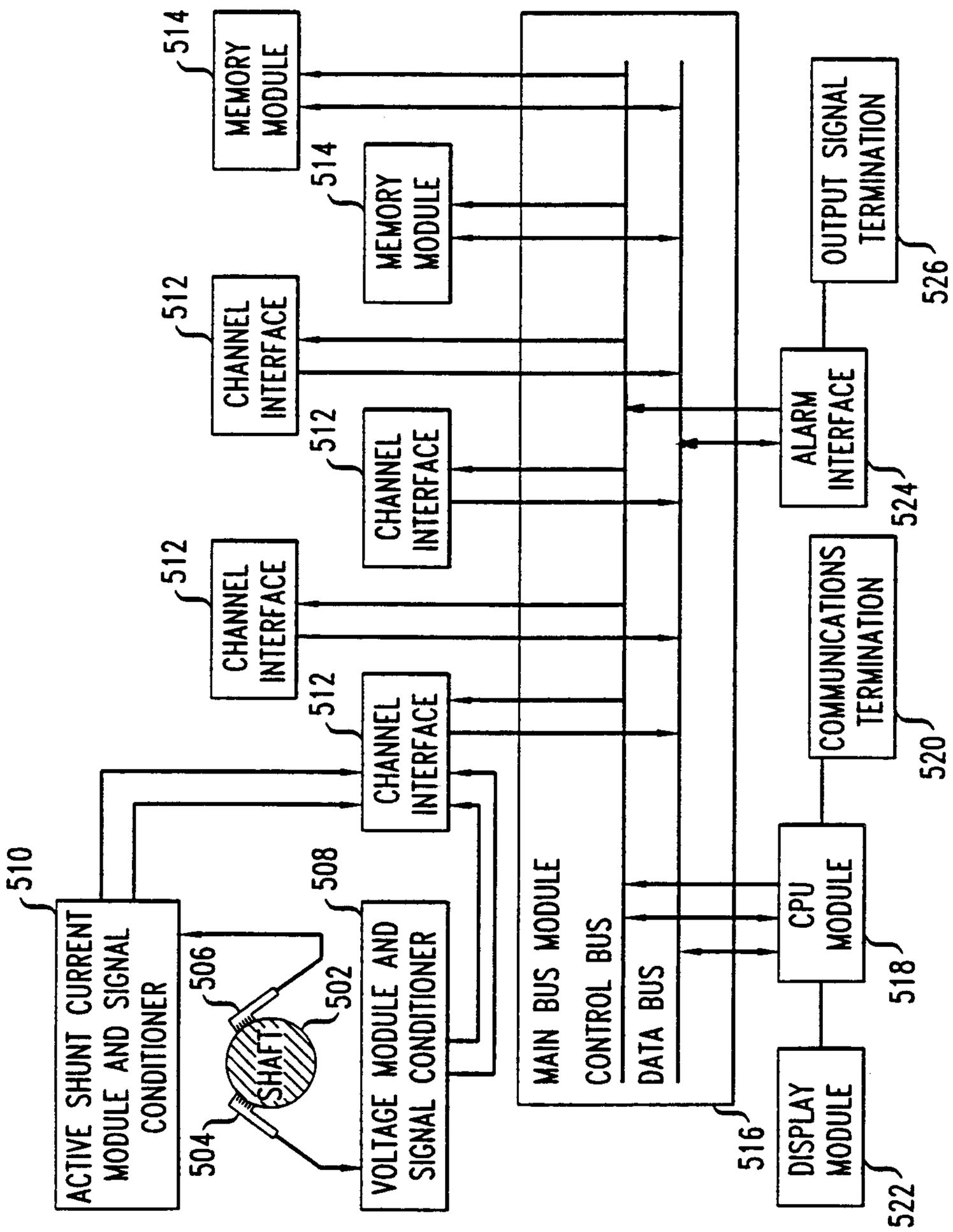

MEMORY MODULE
514
CHANNEL INTERFACE
512
OUTPUT SIGNAL TERMINATION
526
ALARM INTERFACE
524
COMMUNICATIONS TERMINATION
520
CPU MODULE
518
MAIN BUS MODULE
CONTROL BUS
DATA BUS
516
DISPLAY MODULE
522
ACTIVE SHUNT CURRENT MODULE AND SIGNAL CONDITIONER
510
VOLTAGE MODULE AND SIGNAL CONDITIONER
508
SHAFT
502
504
506

FIG. 6

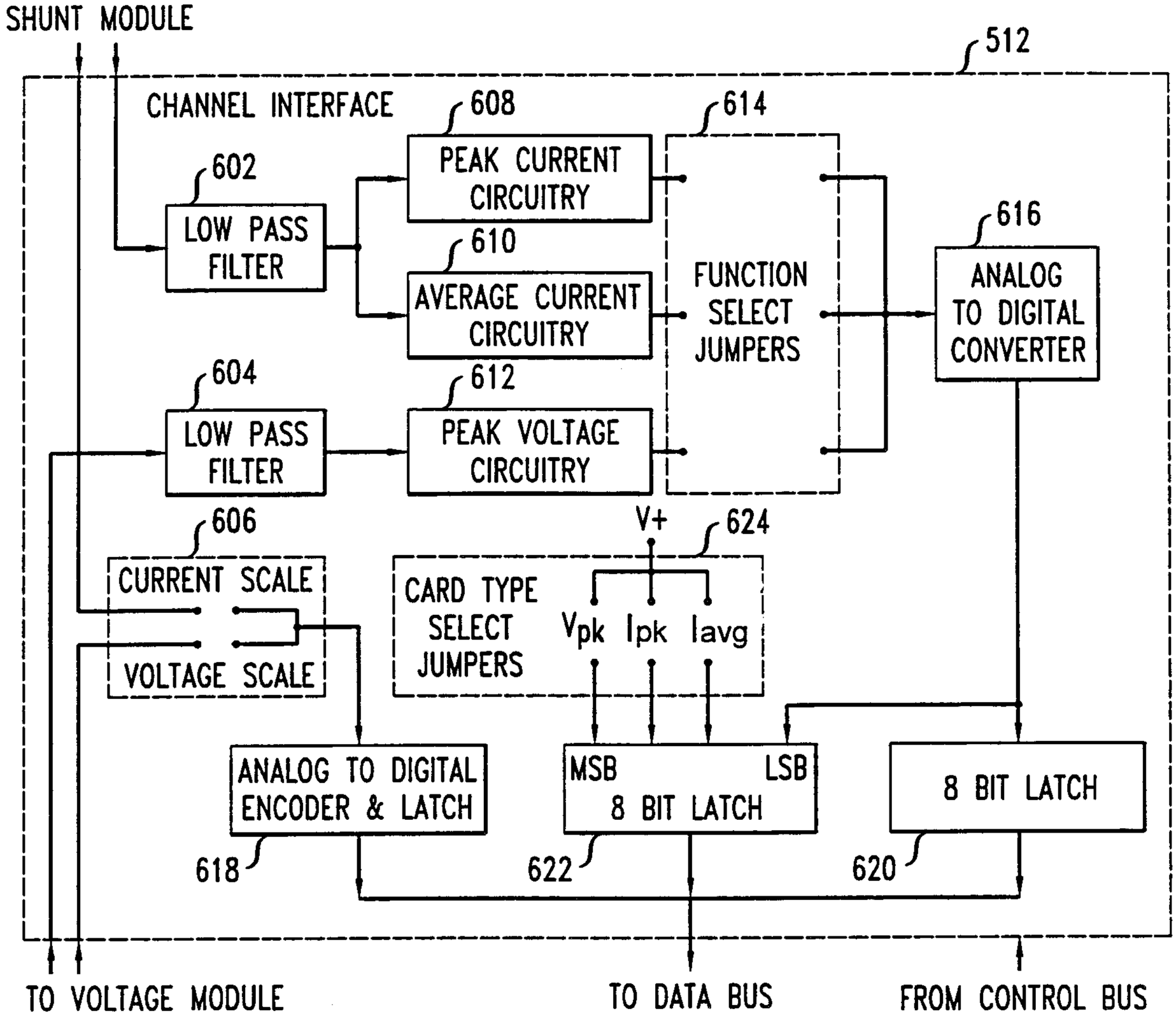
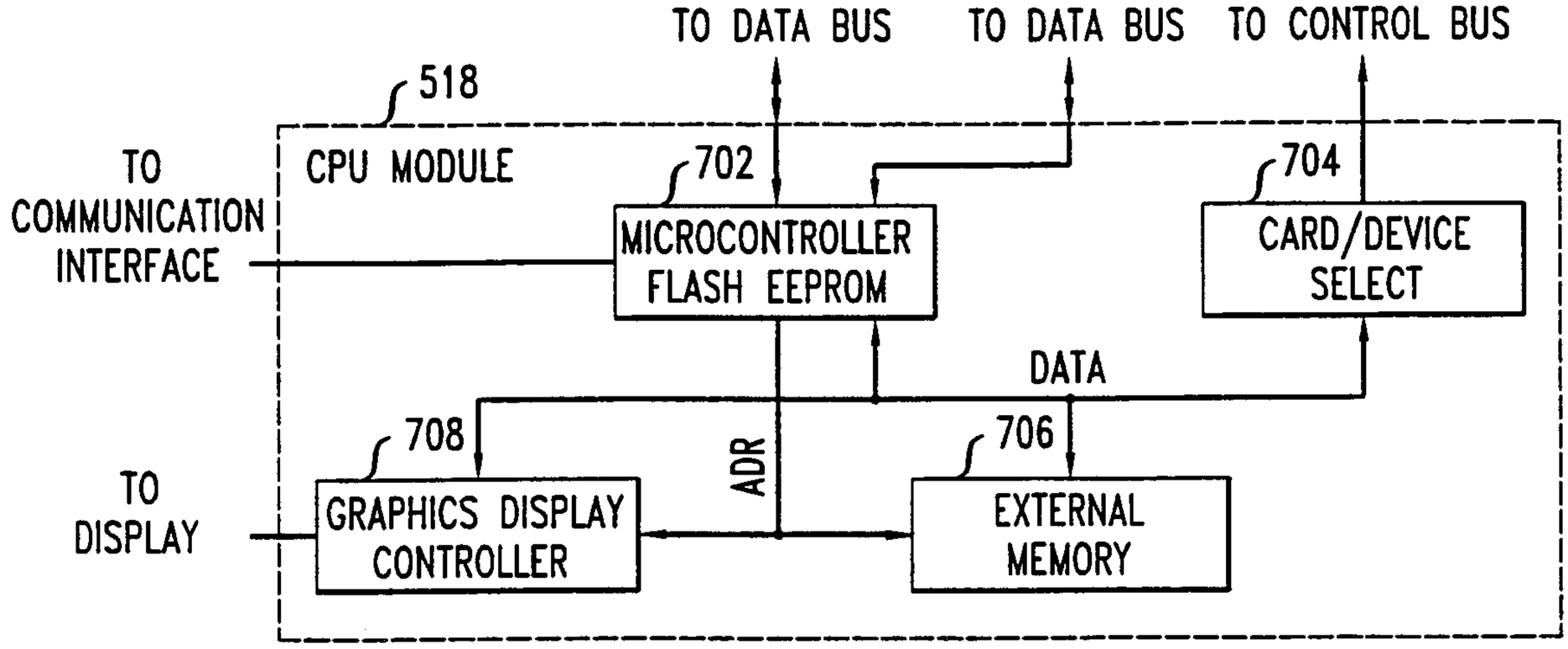
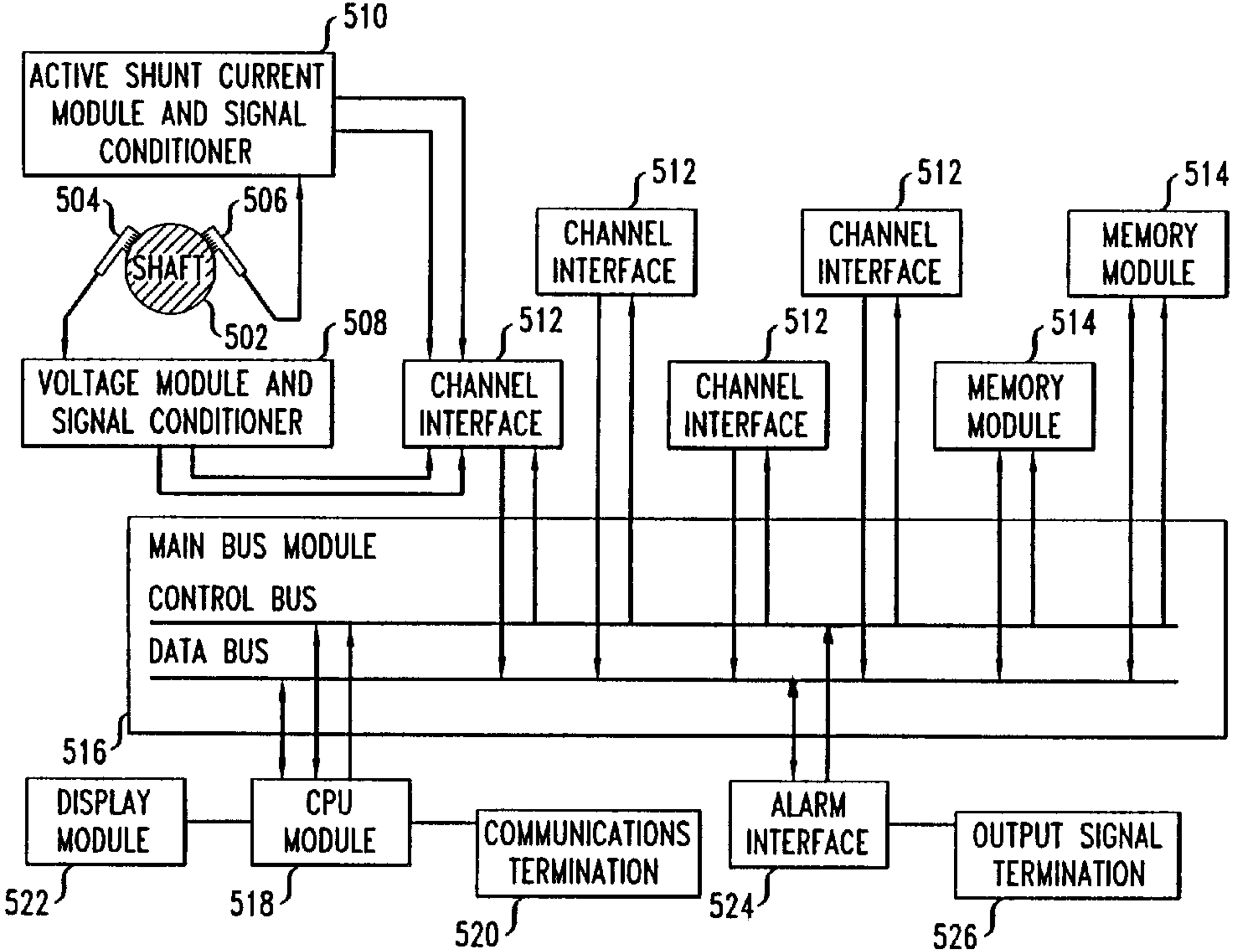

TO ACTIVE SHUNT MODULE
512
CHANNEL INTERFACE
608
614
602
PEAK CURRENT CIRCUITRY
LOW PASS FILTER
610
AVERAGE CURRENT CIRCUITRY
FUNCTION SELECT JUMPERS
616
ANALOG TO DIGITAL CONVERTER
604
612
LOW PASS FILTER
PEAK VOLTAGE CIRCUITRY
606
V+
624
CURRENT SCALE
CARD TYPE SELECT JUMPERS
Vpk
Ipk
Iavg
VOLTAGE SCALE
ANALOG TO DIGITAL ENCODER & LATCH
MSB
LSB
8 BIT LATCH
8 BIT LATCH
618
622
620
TO VOLTAGE MODULE
TO DATA BUS
FROM CONTROL BUS

FIG. 7


TO DATA BUS
TO DATA BUS
TO CONTROL BUS
518
CPU MODULE
TO COMMUNICATION INTERFACE
702
MICROCONTROLLER FLASH EEPROM
704
CARD/DEVICE SELECT
DATA
708
706
ADR
TO DISPLAY
GRAPHICS DISPLAY CONTROLLER
EXTERNAL MEMORY


510
ACTIVE SHUNT CURRENT MODULE AND SIGNAL CONDITIONER
504
506
SHAFT
502
508
VOLTAGE MODULE AND SIGNAL CONDITIONER
512
CHANNEL INTERFACE
512
CHANNEL INTERFACE
512
CHANNEL INTERFACE
514
MEMORY MODULE
512
CHANNEL INTERFACE
514
MEMORY MODULE
MAIN BUS MODULE
CONTROL BUS
DATA BUS
516
DISPLAY MODULE
522
CPU MODULE
518
COMMUNICATIONS TERMINATION
520
ALARM INTERFACE
524
OUTPUT SIGNAL TERMINATION
526