

- [54] METHOD AND APPARATUS ANALYZING AND MONITORING THE PERFORMANCE AND OPERATION OF MACHINES AND PROCESSES DRIVEN BY ELECTRICAL MOTORS
- [76] Inventors: **Leonard J. Higgins**, Hatlee Rd., Jonesville, N.Y. 12019; **Richard Jay Murphy**, R.D. No. 3, Tiffault Rd., Ballston Spa, N.Y. 12020; **Rajendran Ramachandran**, 24 Barceloma Dr., Elnora, N.Y. 12065
- [22] Filed: **Aug. 9, 1972**
- [21] Appl. No.: **279,090**
- [52] U.S. Cl. **235/151.3, 340/267, 235/92 PD, 324/71**
- [51] Int. Cl. **G01n 19/02**
- [58] Field of Search **73/133, 104; 235/151.3, 235/151.1, 92 PD, 92 QC; 324/71, 76, 142; 83/72, 74, 75, 76**

[56] **References Cited**

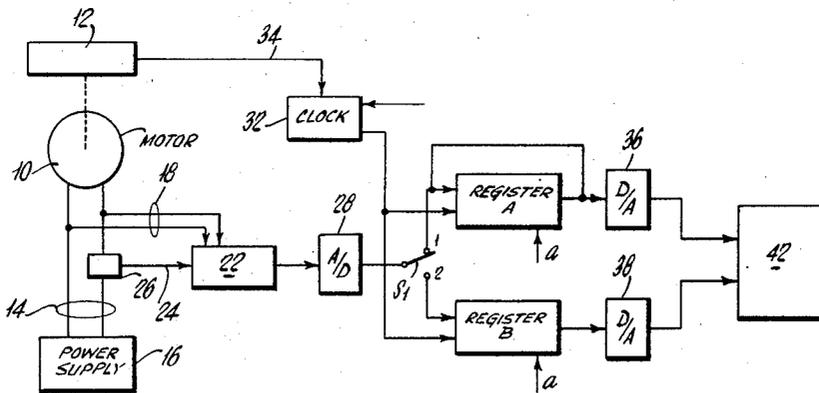
UNITED STATES PATENTS

3,257,652	6/1966	Foster	340/213
3,329,806	7/1967	McCauley.....	235/92 PD
3,346,725	10/1967	Allured et al.....	235/92 PD
3,579,217	5/1971	Casey et al.	340/267 X
3,604,904	9/1971	Stiebel et al.....	235/92 PD
3,683,160	8/1972	Windley.....	235/151.3 X
3,689,839	9/1972	Cother	324/71 R
3,694,637	9/1972	Edwin et al.....	235/151.3

Primary Examiner—Malcolm A. Morrison
Assistant Examiner—Edward J. Wise

[57] **ABSTRACT**
 The specifications and drawings disclose a novel method and apparatus for monitoring the operation of machines and processes driven by electric motors. The true power applied to the motor during an operating cycle is measured and changes in this power relative to a standard are correlated with specific operating parameters.

4 Claims, 9 Drawing Figures



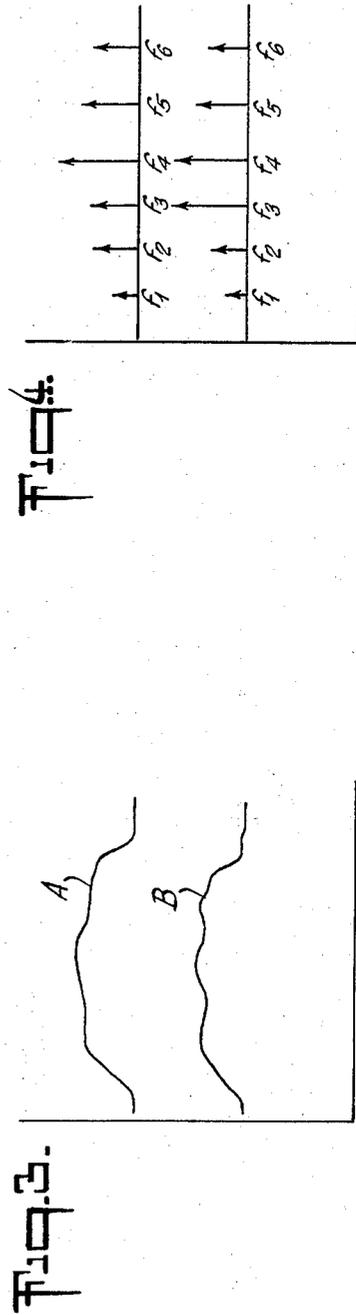
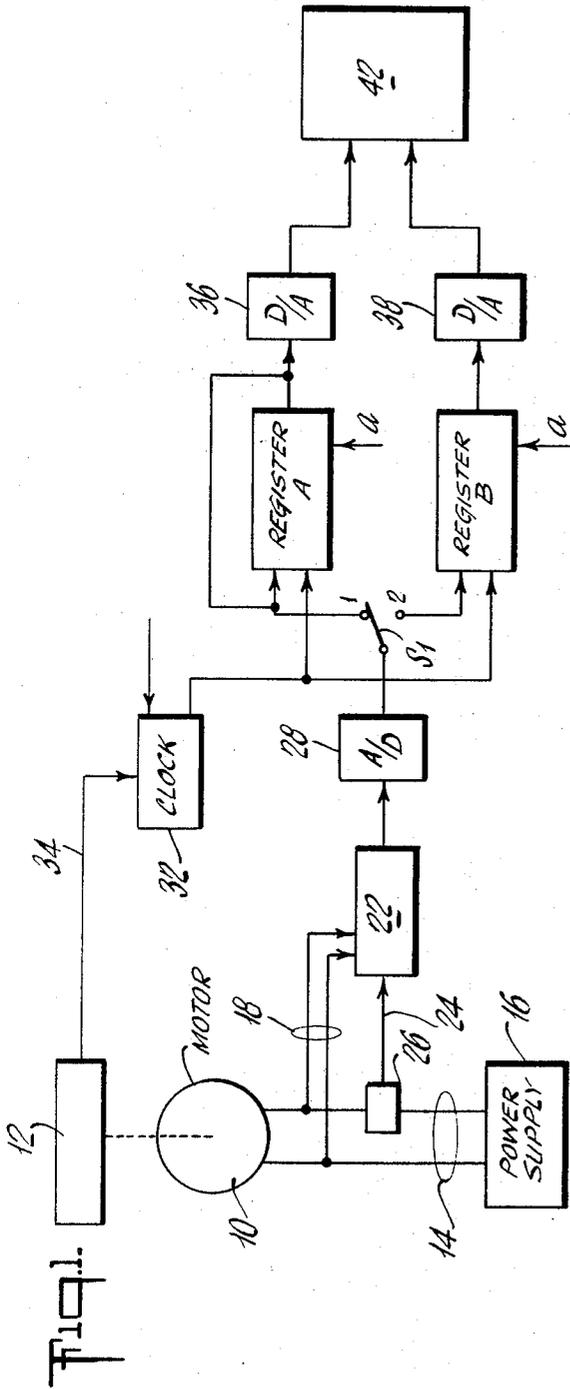


Fig. 2.

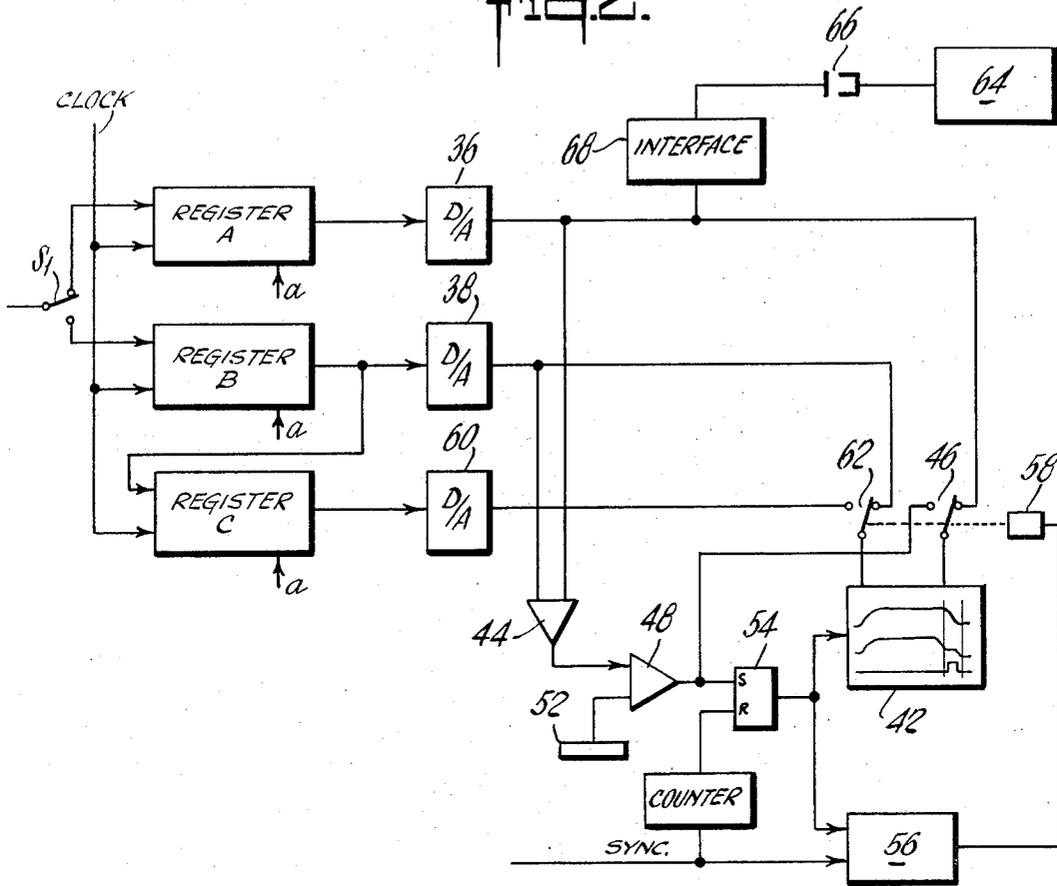


Fig. 5.

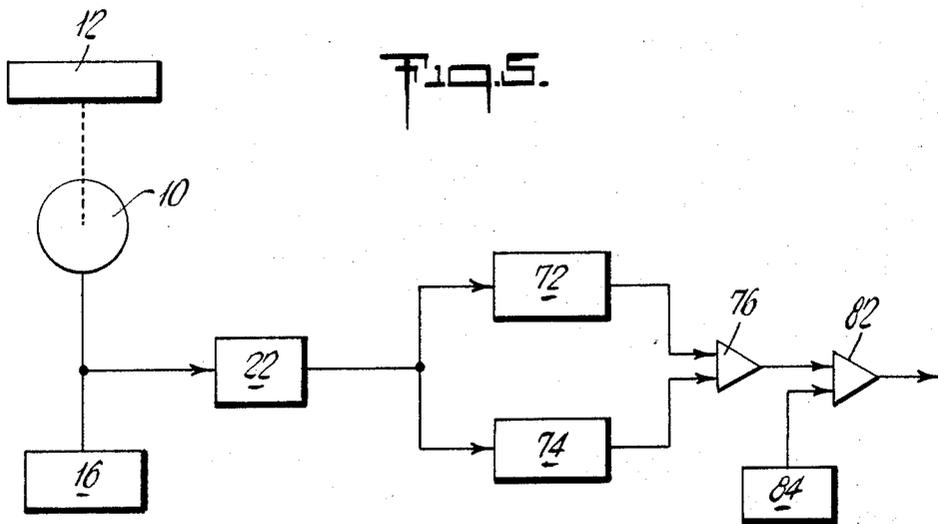


Fig. 6.

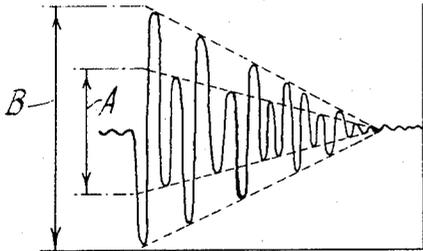


Fig. 7.

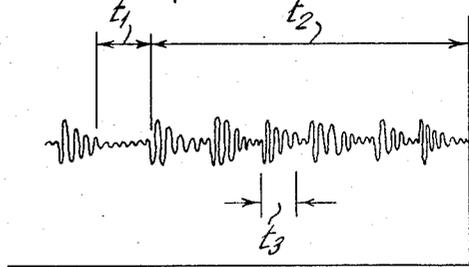


Fig. 8.

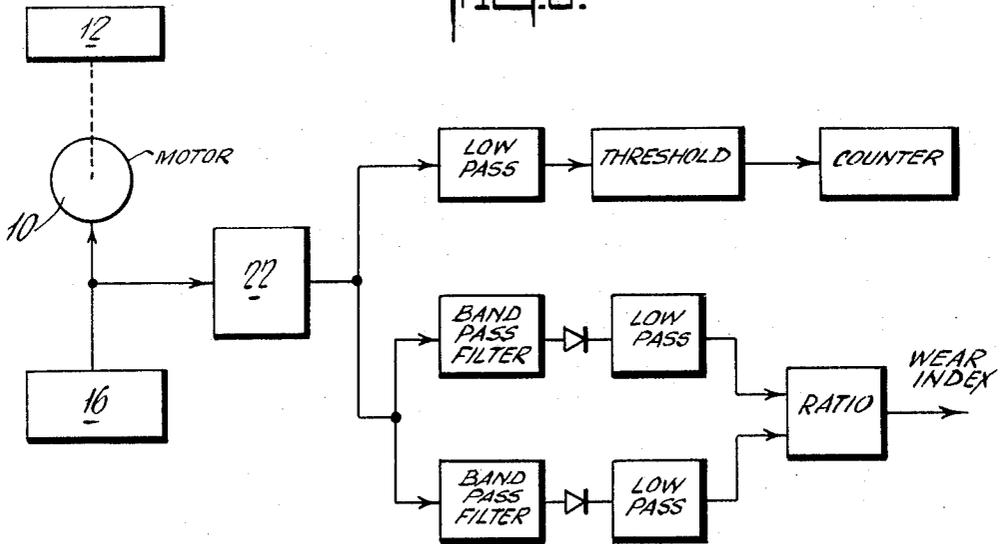
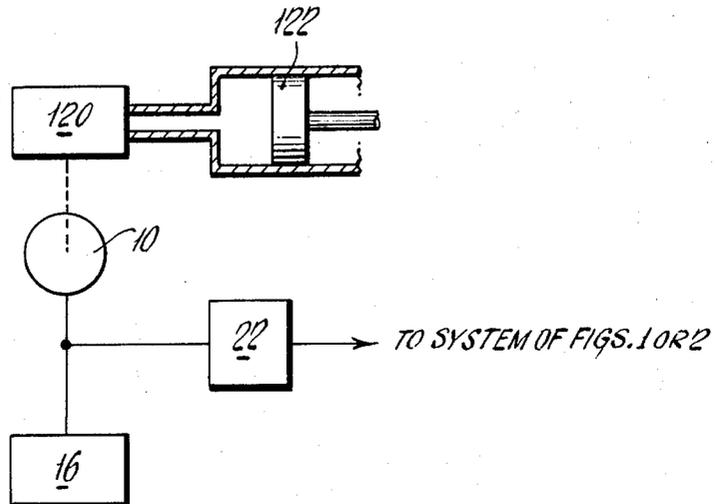


Fig. 9.



**METHOD AND APPARATUS ANALYZING AND
MONITORING THE PERFORMANCE AND
OPERATION OF MACHINES AND PROCESSES
DRIVEN BY ELECTRICAL MOTORS**

BACKGROUND OF THE INVENTION

This invention relates to an improved method and apparatus for analyzing and monitoring the performance and operation of machines and processes driven by electric motors, and more particularly relates to the identification and monitoring of motor power characteristics indicative of one or more specific operational parameters.

A widely used prior art approach to measuring and monitoring various characteristic of a machine or process operation is to use a variety of transducers to convert different physical quantities such as displacement, pressure, speed and the like to electrical signals. These signals are then used both alone and in combination for monitoring and controlling the machine or processes. In cases where it is not possible or economically practical to measure representative physical quantities, such as the size or finish of a part while it is being made, measurements are made before and after the process to determine if proper materials have been used and if the machine or process operated as intended. Factors such as tool wear are measured indirectly by measuring such things as vibration or noise. Correlations are then attempted between a spectral analysis of such phenomena and the operation of the machine or performance of the process.

These prior art approaches suffer the common disadvantage of requiring many modifications or attachments to the machinery which are cumbersome, expensive, vulnerable to damage, or all of these. Measurements made during machine operation are often not comprehensive enough unless extremely complex equipment is used. Techniques such as spectral analysis of noise or vibration are not always successful because of the interfering effects of machine masses or noise from adjacent operations. Then too, the transducers used are notoriously unreliable and normally unsuited for day to day use in the industrial environment and such techniques, therefore, tend to be restricted to useful research tools.

In addition to attempting to monitor the conditions of a satisfactory process, there is also a need to protect many machines or processes against damage due to overload, improper adjustment, or dull tools and the like. This need has led to the use of devices which measure the current or average power being consumed by a machine or process and is based on an assumption that a defective condition will give rise to a change in the average or peak power or current consumption occurring during operation. Proposals have also been made in the prior art to record the current applied to the machine driving motor during a normal cycle of operation and to compare it with current applied during subsequent operating cycles.

Such prior art methods and apparatus which rely upon current or average power delivered to the drive motor have been limited in this application. For example, the current or average power consumption may be subject to variations of an amount greater than that caused by an abnormality in some cases while in others the peak power may not change significantly in the presence of a deviation from normal operation. In addi-

tion, current actuated devices as used in the prior art are insensitive to power changes at constant voltage which are manifested as changes in power factor. Furthermore, power transducers used previously are unable to function properly if the power factor is appreciably less than unity; it will be appreciated that low power factors are often encountered in industrial machinery and process environments.

SUMMARY OF THE INVENTION

A general object of this invention is the provision of a method and apparatus which economically and reliably overcomes the problems of the aforementioned approaches to control and protection of electrically powered machinery and processes.

More specific objects of the invention include methods and apparatus for monitoring the operation of electromechanical machines and systems such as metal cutting machines including; rotating and translating multi-tooth and single-tooth cutter, milling machines, drilling machines and metal forming machines such as reciprocating presses and stamping and drawing presses.

Another object of the invention is the provision of a novel method and apparatus for monitoring electrohydraulic machines and systems such as injection molding machines and powder metallurgy presses.

Still another object of the invention is the provision of a novel method and apparatus for counting parts produced by a machine. Other objects and advantages of the invention will become readily apparent from the following description and claims.

Briefly, the invention contemplates the provision of a method and apparatus for monitoring the performance of machines and processes driven by electric motors in which a characteristic change in true power applied to the drive motor is identified and correlated to the parameter being measured for a particular machine or process. The reaction effect of various events, such as the work done by a machine, is reflected by changes in the instantaneous input power to the driving motor. Deviations in the various physical parameters such as an increase in the impact loading of a press, or degeneration of the proper chipforming capability of a metal cutting tool, or changes in synchronization of various events in a machine process, or changes in material quality or quantity, and most other significant occurrences in a machine or process cycle cause corresponding signifying alterations of the power demand with time. The signifying characteristic may be a change in magnitude of applied power at one instant relative to the applied power at another instant during the cycle, the appearance of or modification of certain characteristic frequency components of the applied power, or changes in the amount of power demanded during specific intervals of time. The invention therefore contemplates detecting the true current or true power variations with time, independent of changes in power factor and with a frequency response which is adequate to observe the most rapid significant transients associated with events of interest; separating and observing such variations, and comparing observed variations with a standard. The use of the invention permits the effective monitoring of entire machinery or process cycles, the control or optimization of all or part of a machinery process by feedback control or the measurement of specific parameters associated with a work process, such as indices of tool wear, density, quantity, hard-

ness, viscosity or other qualities of processed material during the actual performance of conversion of the material.

THE DRAWINGS

Having briefly described this invention, it will be described in greater detail along with other objects and advantages in the following detailed description of a preferred embodiment which may be best understood by reference to the accompanying drawings. These drawings form part of the instant specification and are to be read in conjunction therewith. Like reference numerals are used to indicate like parts in the various views, in which:

FIG. 1 is a block diagram of apparatus in accordance with the teaching of the invention for determining significant characteristics of a machine or process driven by an electric motor;

FIG. 2 is a block diagram of an alternate embodiment of apparatus in accordance with the invention;

FIG. 3 shows idealized waveforms of two cycles of instantaneous power applied to a motor;

FIG. 4 represents the frequency spectral components of the waveforms shown in FIG. 3;

FIG. 5 is a schematic diagram of apparatus for monitoring a specific parameter of machine performance;

FIG. 6 is the waveform of the power applied to the drive motor of a gear cutting machine;

FIG. 7 is the waveform of the gear cutter showing two complete cycles of operation;

FIG. 8 is a schematic diagram of an exemplary circuit of the invention for counting parts and for monitoring tool sharpness;

FIG. 9 is a block diagram of apparatus in accordance with the invention for monitoring a hydraulically operated injection molding machine.

DESCRIPTION OF THE INVENTION

Referring now to FIG. 1 of the drawings, an electric drive motor 10 is operatively coupled to a machine or process indicated by block 12. The machine or process 12 can be virtually any machine or process known in the art which is operated by an electric motor such as a metal cutting machine, or an injection molding machine, as just two examples. In the case of a hydraulically operated injection molding machine, the motor 10 could be the compressor motor.

Leads 14 couple a power supply 16 to the motor 10. The power supply may be direct or alternating current supply and in the case of an alternating supply may be a single phase or three phase supply. Regardless of the type motor employed or the type of supply, it is important to measure the instantaneous power applied to the motor. One satisfactory technique known to those skilled in the art employs Hall effect devices. In another satisfactory technique, operational amplifiers are used to multiply the instantaneous current and voltage. Integrated circuit analog multiplier circuits satisfactory for this purpose, are commercially available. In the illustrative embodiment of FIG. 1 a multiplier 22 is employed; leads 18 couple the instantaneous voltage applied to the motor 10 as one input to multiplier 22, and a lead 24 couples the output of a current sensing transducer 26 as its other input.

To permit flexibility in handling and analyzing the data related to the instantaneous power applied to the motor during an operating cycle, it is advantageously

stored digitally. To this end the output of multiplier 22, which is proportional to the instantaneous power applied to the motor 10, is coupled as an input to an analog to digital converter 28. A switch S_1 couples the binary output of converter 28 to shift register A when it is in position 1 and to a shift register B when in position 2. The sampling rate of the converter 28 should be sufficient to provide a frequency response satisfactory to store the highest transient of interest.

Register A stores the power applied to the motor during a normal or standard cycle of operation and this information is used as a basis for determining characteristic signatures of operating parameters or for monitoring the operation during subsequent cycles. Register B stores information from subsequent operating cycles. It should be noted that register A has a connection 29 between its output and input to refresh the stored information as it is read out. Further, as will be readily appreciated by those skilled in the art, the registers may be reset by means of suitable signal input at a .

The position of data in each register is advanced, and thusly controlled, by a suitable clock pulse generator 32. So that the information stored in corresponding locations in registers A and B represents the power applied at the same point in each machine cycle, synchronizing signals on lead 34 synchronize the clock pulses with the machine cycle and provide an index pulse at the start of each cycle. Any of a number of suitable transducers known in the art may be used to generate the synchronizing pulses.

Digital to analog to converters 36 and 38 convert the information in registers A and B respectively to analog signals which are coupled to a display apparatus 42 that is capable of simultaneously displaying both signals for side-by-side comparison. Dual trace storage oscilloscopes or dual trace strip chart recorders are satisfactory for this purpose.

In a typical operation, switch S_1 is connected to terminal 1 and the machine is run through one cycle. The instantaneous power applied to the motor 10 is stored in register A in the form of binary numbers for use as a basis for analyzing machine operation and comparison with subsequent operating cycles. With the switch in position 2 the machine is run through subsequent cycles of its operation, and the instantaneous power applied to the motor 10 during each cycle is temporarily stored in register B. The information contents of registers A and B are simultaneously displayed on the screen of oscilloscope 42, permitting and facilitating side-by-side comparison and observation of the effect of known changes in machine or process operation or to permit and facilitate monitoring of machine operation. It should be noted, if desired, more complex and powerful comparisons of the information can be performed by feeding the outputs of registers A and B to a digital computer. Further, with certain additional apparatus, differences exceeding a certain magnitude can be detected automatically. FIG. 2 illustrates such an embodiment.

In the embodiment of FIG. 2 the input to switch S_1 can be identical to that shown in FIG. 1 and for this reason it has not been shown. In this embodiment, the contents of registers A and B are coupled to display apparatus 42 if the instantaneous power applied to the motor at a point of a cycle differs from the standard by more than a predetermined amount. In addition, the

difference signal can also be recorded in juxtaposition to the abnormal cycle.

To these ends the outputs of converters 36 and 38 are coupled as input to a difference amplifier 44. The output of amplifier 44 is coupled to one input of a second operational amplifier 48 whose other input is coupled to a variable reference potential 52. Amplifier 48 produces an output whenever its input exceeds a value established by reference 52.

The output of amplifier 48 is used to set a flip flop 54 and is also coupled to an input terminal 46 for the display 42. When set, flip flop 54 activates the display 42 and, via a suitable logic circuit 56 and switch 58, couples the outputs from converters 36 and 38 to the display apparatus 42. Flip flop is reset by a signal from counter 40 after a desired number of machine cycles indicated by the synchronizing index pulse.

Register B is cross-coupled to a third register C, permitting any abnormal cycle to be redisplayed in juxtaposition output from amplifier 48. A digital to analog converter couples the output of register C to an input terminal 62 of the display. After one complete cycle has been displayed as determined by the synchronizing index signal, switch 58 connects terminals 46 and 62 to the inputs of display device 42 and the contents of register C, the abnormal cycle, are recorded along with the difference signal output from amplifier 48, permitting rapid identification of that point in the cycle where the deviation occurred.

If desired, diagnostic information can be recorded on or played back from a magnetic cassette recorder 64. A suitable plug 66 and logic interface 68 connects the recorder to the system. When connected, information may be recorded on the cassette, or information previously recorded may be displayed for diagnostic purposes.

It will be appreciated that the performance of the machine can be monitored directly with the apparatus of FIGS. 1 and 2. In addition, they can be used advantageously in determining the characteristic signature of a machine. Referring now to FIG. 3, the curve A represents the waveform of instantaneous power applied to the drive motor of a machine operating in an acceptable manner. Curve B represents the waveform instantaneous power applied to the motor during a cycle in which one or more machine operating parameters have changed in some known fashion. In FIG. 4, D represents the frequency spectrum of the components of waveform A at frequencies f_1 through f_6 and curve E represents the same thing for waveform B.

In the illustrated example of FIGS. 3 and 4, it will be noted that the greatest change between waveforms A and B occurs at frequency f_3 and that there is no discernible change at frequency f_1 . Thus, a machine may be monitored for a specific parameter by this instantaneous power applied to its drive motor during a cycle.

This may be accomplished by comparing the component of power at one frequency with the component at another frequency, either by means of a digital computer or by means of analog filters.

FIG. 5 illustrates an embodiment employing filters. The instantaneous power to the drive motor 10 is measured as explained in connection with FIG. 1. The output of multiplier 22 is coupled as an input to two band pass filters 72 and 74 whose outputs are coupled as inputs to a difference amplifier 76.

Preferably, the passbands of filters are narrow with the center of the passband of one at a frequency where there is a relatively large change in the component of power (f_3 in the illustrated example) and the center of the other at a frequency where there is little change (f_1 for example).

A signal indicative of a change which exceeds a predetermined amount in the output of filter 72 relative to the output of filter 74 is generated by coupling the output of difference amplifier 76 as one input to a second differential amplifier 82. Its other input is coupled to a reference potential source 84. Thus amplifier 82 produces a characteristic signal output indicative of a change in a particular operating parameter. This signal may be used to control the process, or provide an indication for an operator, or both.

It should be noted that the frequencies f_1 and f_3 may vary throughout a band during repeated machine operations. Sophisticated techniques well known to those skilled in the electronics art, may be employed to track these signature frequencies: phase locked oscillators, for example. Further, by using a digital computer or other suitable apparatus, the components of the instantaneous power at a number of frequencies can be analyzed and compared both among themselves and with other standards if desired. In this manner a thorough and complete analysis of the operation of the machine can be obtained. Then too, it should be noted that the information obtained can be used to control or modify the machine or process.

The principles of this invention can also be employed to provide an accurate and virtually foolproof parts count (for example, the number of gears cut by an automatic gear cutting machine) in addition to monitoring the operation of one or more machine parameters. FIG. 6 shows the waveform of instantaneous power applied to a gear cutting machine. In this illustrative example, six teeth are cut to form each gear. FIG. 7 shows the waveform of FIG. 6 on a reduced scale. The waveform is repeated six times in close succession, once for each tooth. Time t_1 is the time required to remove a completed gear and insert a new blank, time t_2 is the time required to complete the six cuts, and time t_3 the time required to cut a single tooth. It should be noted that magnitude of the signal during the time t_1 is the magnitude of signal when no part is being produced.

The actual waveform illustrated in FIG. 6 has an outer envelope and an inner envelope as indicated by the broken lines. The magnitude of these envelopes at the end of a cut are represented by the letters B and A respectively. It has been determined by observation that the ratio of the magnitude of B to A increases with increasing tool wear.

FIG. 8 is a circuit for counting the number of gears cut by a machine 12 and for providing an index of the wear of its cutting tool. The output of multiplier 22 is the instantaneous power applied to the motor 10 as previously explained. In order to obtain a completed parts count, this output is coupled to a low pass filter 92 which integrates the signals required for the completion of each gear. This integrated output is a series of pulses as shown at P, one for each completed gear. A wave shaping and thresholding circuit 94 provides a series of pulses indicative of the number of finished gears and these pulses are counted by a counter 94.

To obtain an index of tool wear, the output of multiplier is coupled in parallel to the inputs of narrow band

pass filters 102 and 104. The pass band of filter 102 is centered at the nominal frequency of the waveform component within the envelope A. Filter 104 is similarly centered for component within envelope B. To provide a direct current level proportional to ratio A envelope waveform relative to the B envelope, diodes 106 and 108 respectively couple the outputs of filters 102 and 104 to the inputs of a pair of low pass filters 112 and 114. Filters 112 and 114 integrate the half wave rectified output of filters 102 and 104 respectively, providing outputs which are proportional to the magnitudes of the A envelope and B envelope signals. A suitable resistive network 116 or other suitable circuit known in the art provides a signal output which is proportional to the ratio of the A and B envelopes, and thus provides an index of tool wear.

The principles of this invention are applicable to hydraulically operated machines where the compressor is driven by an electric motor. FIG. 9 shows an exemplary embodiment of such a system. Here the motor 10 is coupled to a compressor 120 which in turn drives a ram 122, for example. By coupling the output of multiplier 22 to a system of the type shown in FIG. 1 or FIG. 2, the operating parameters of system such as materials temperature, and the like can be determined readily.

Although the present invention has been described with reference to a specific embodiment, it will be appreciated that a variety of changes may be made without departing from the scope of the invention. Certain features may be used independently and equivalents may be substituted. For example, in certain applications it may be satisfactory to detect the instantaneous current applied to the motor instead of the instantaneous power and in other cases it may be satisfactory to detect the instantaneous power factor of the motor. Furthermore, the detection of changes as exemplified by the methods described herein leads directly to the ability to automatically adjust processes driven by electric motors using feedback controls well known in the art. Thus the scope of the invention encompasses the scope of control of machines and processes using the analyzing and monitoring apparatus described to generate a feedback or control signal or reference in control system.

What is claimed is:

1. A method of determining the characteristics signature of a machine driven by electric motor including the steps:

- measuring the electric power applied to the drive motor during a standard operating cycle of the machine;
- storing the information with respect to the frequency spectrum distribution of power applied to the motor during standard operating cycle;
- changing one or more of the machine operating parameters required for standard operation;
- measuring the power applied to the drive motor during an operating cycle in which said one or more parameters has been varied;
- storing the information with respect of the frequency spectrum distribution of power applied to the motor during the operating cycle in which one or

- more parameters has been varied;
- comparing the information concerning frequency spectrum distribution of power for a standard operating cycle with the information concerning frequency spectrum distribution of power for an operating cycle in which said one or more parameters has been varied;
- determining from the comparing step components of power which exhibit relatively small changes during the operating cycle in which one or more parameters has been varied as compared with the standard operating cycle; and
- determining from the comparing step components of power which exhibit relatively large changes during the operating cycle in which one or more parameters has been varied as compared with the standard operating cycle.

2. A method for monitoring the operation of a machine driven by an electric motor, comprising the steps:

- measuring the power applied to the motor during an operating cycle of the machine;
- detecting a first component of said power applied to the motor during the operating cycle;
- detecting a second component of said power applied to the motor during the operating cycle; and
- comparing first and second components to detect changes in the relative magnitudes of said first and second components which exceed a predetermined amount.

3. A method for determining the characteristics signature of a machine or process driven by an electric motor, as in claim 2, wherein said comparing step includes comparing the frequency spectrum distribution of power components for the operating cycle in which one or more parameters has been varied with the frequency spectrum distribution of power components for the standard operating cycle.

4. Apparatus for monitoring of a machine or process driven by an electric motor comprising in combination:

- means for measuring the power applied to the motor producing an output signal indicative of the applied power;
- a first narrow, band-pass filter means coupled to receive said output signal and produce a signal output proportional to the magnitude of a component of applied motor power which changes relatively slightly with change in a machine operating parameter;
- a second narrow, band-pass filter means coupled to receive said output signal and produce a signal output proportional to the magnitude of a component of applied motor power which changes relatively greatly with a change in said machine operating parameter;
- means for comparing the output signals of said first and second band-pass filters; and
- means for detecting when the difference in said filter outputs exceeds a predetermined amount.

* * * * *