Jan. 14, 1964 E. MITTELMANN 3,117,919

ELECTRIC SUPPLY SYSTEM FOR ELECTROLYTIC GRINDING

Original Filed Sept. 21, 1953 3 Sheets-Sheet 1

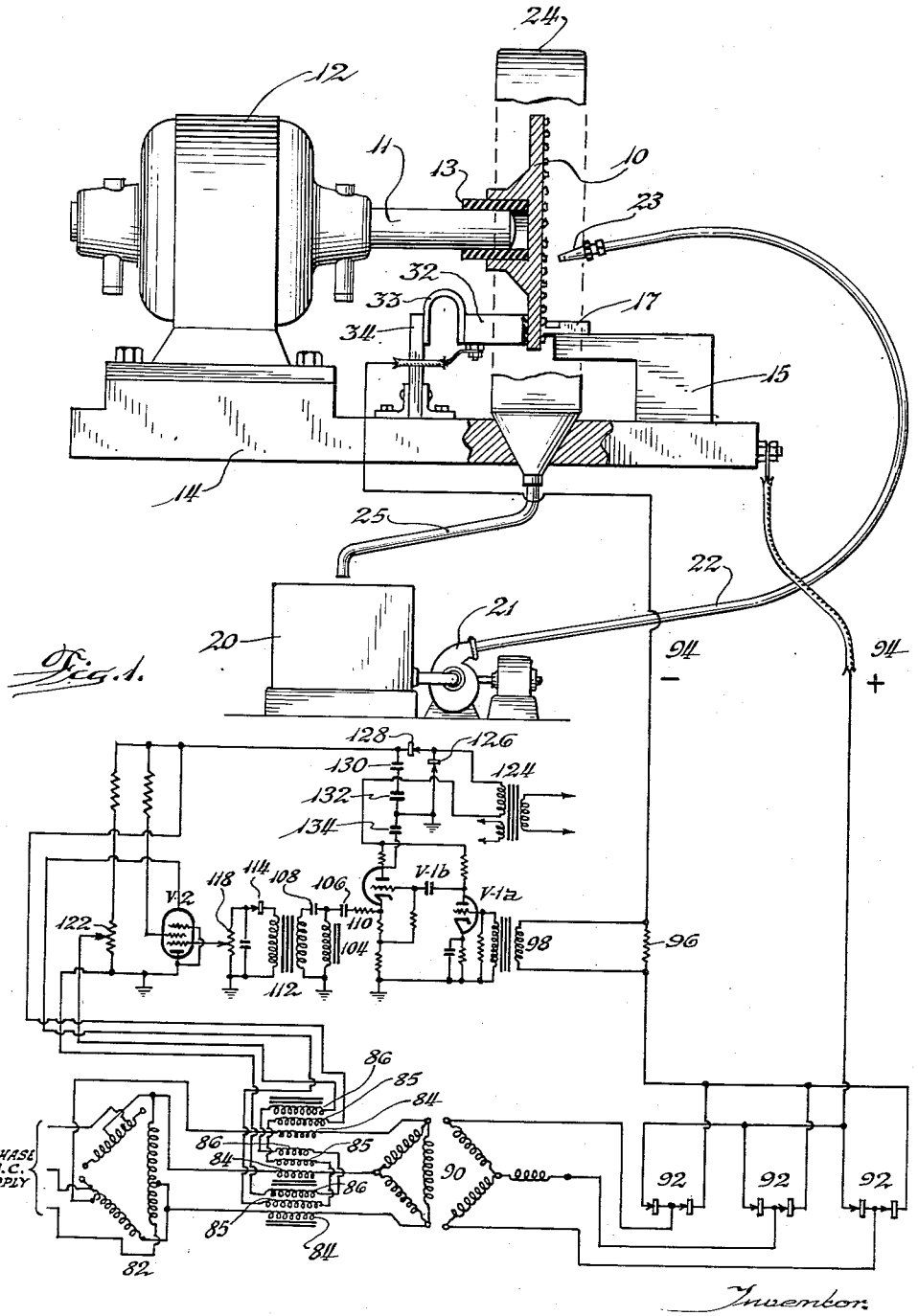


Fig. 1.

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ELECTRIC SUPPLY SYSTEM FOR ELECTROLYTIC GRINDING

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Fig. 2.

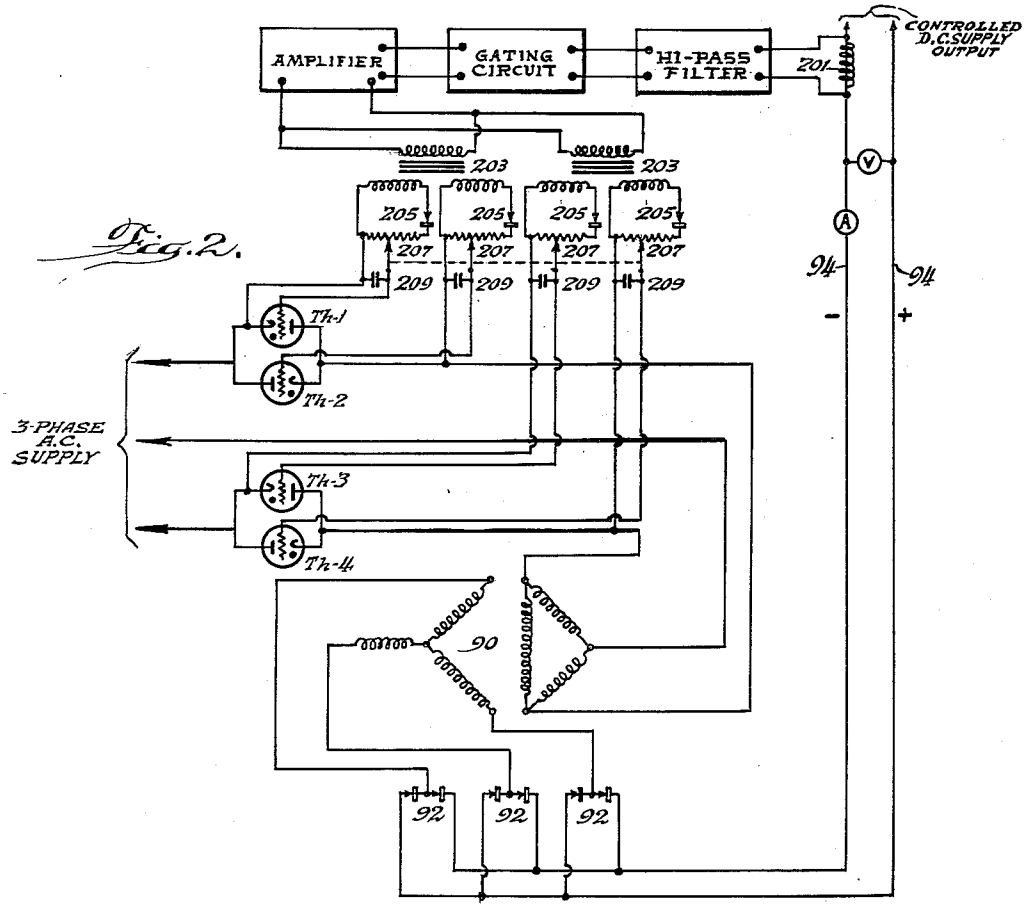
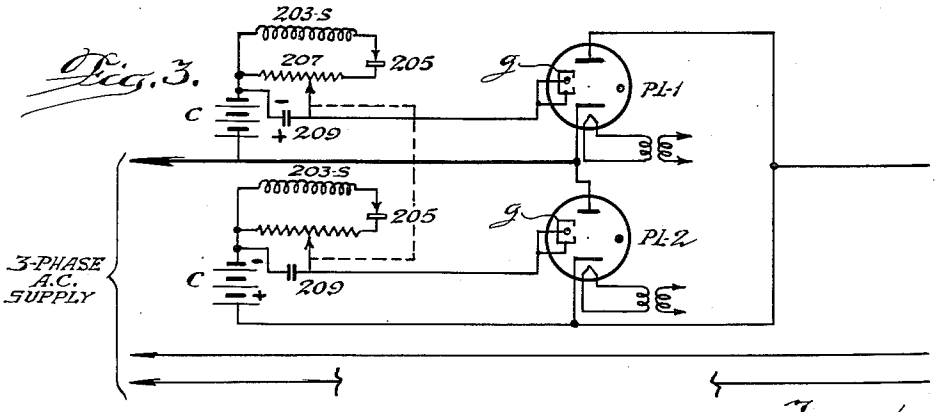


Fig. 3.



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ELECTRIC SUPPLY SYSTEM FOR ELECTROLYTIC GRINDING

Original Filed Sept. 21, 1953 3 Sheets-Sheet 3

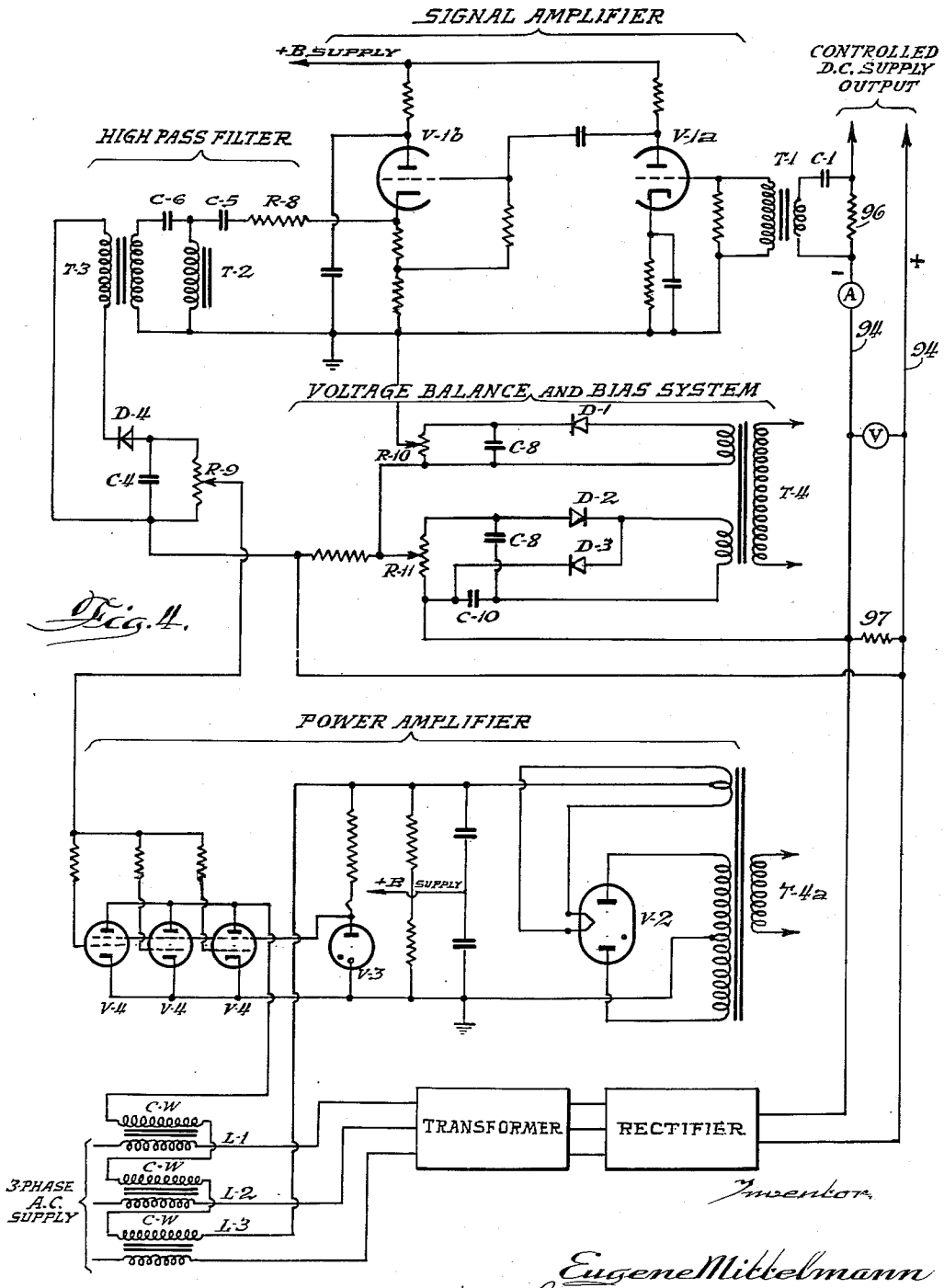


Fig. 4.

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United States Patent Office 3,117,919 Patented Jan. 14, 1964

3,117,919

ELECTRIC SUPPLY SYSTEM FOR ELECTROLYTIC GRINDING

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Continuation of application Ser. No. 381,278, Sept. 21, 1953. This application Feb. 10, 1961, Ser. No. 89,603
24 Claims. (Cl. 204—218)

This invention relates to apparatus and circuits for supplying and controlling electrical energy for electrolytic grinding.

This application is a continuation of applicant's copending application Serial No. 381,278, filed September 21, 1953, now abandoned. Certain of the subject matter disclosed herein is claimed in U.S. Patent No. 2,826,540, issued March 11, 1958, to George F. Keeleric, and in the copending application of George F. Keeleric, Serial No. 700,493, filed December 3, 1957, now Patent No. 3,004,910, which latter application is a division of the application which matured into the said patent.

The object of this invention is to provide an adjustable and automatically controlled electrical system and circuitry therefor for supplying current for electrolytic grinding operations.

With the increased use of hard materials, such as the sintered metal carbides, as tools or in high temperature applications, such as the blades of jet engines (where titanium carbide is sometimes used), the problem of shaping such materials, always troublesome, has become of major importance. It has been common in the past to use diamond bearing abrasive tools for this purpose, but such tools are costly. Moreover, even the best of such processes is slow. If the effort is made to accelerate the grinding operation—for example, by increased pressure of the part to be shaped against the tool—the result is to increase the rate of wear of the grinding tool, and thus add to that cost.

As disclosed in the aforementioned copending application, it is possible to shape or "grind" such hard materials by electrolytic action between the part to be shaped and a grinding electrode. In this process an electrolyte is applied over the surface of the grinding tool and an electric current is passed through the electrolyte in a direction to make the workpiece an anode. Commonly, the grinding tool has, on its working face, numerous particles of diamond bort or other abrasive. The grinding tool or electrode is made of metal and serves as the opposite electrode or cathode in the electrolytic circuit between the workpiece and the grinding tool.

The abrasive particles serve to remove non-conductive films which may form on the surface which is being shaped, and may serve also to provide abrasive cutting action. By this conjoint electrolytic and abrasive action, the cutting speed is very much enhanced as compared with that obtained by diamond grinding alone. On the other hand, it is also possible to rely almost entirely upon electrolytic action, thereby reducing the rate of wear on the abrasive particles to a very minimum. This procedure will be followed at times when diamond bort is extremely scarce, even at the expense of some reduction in cutting speed.

The optimum operation of the electrolytic process depends upon a number of factors. A suitable electrolye must be used. Such electrolytes are described in the aforementioned copending application. The amount of protrusion of the abrasive particles from the metal portion of the grinding tool must be kept within limits ranging from .0005" up to a maximum of about .010". The spacing and density of abrasive particles is another important factor. For various kinds and grades of materials

to be shaped, the grit size of the abrasive particles will be of importance.

But, assuming that these factors are within the proper limits, a very great difference in removal rate will result from a proper control of the current supplied to the electrolytic system. The rate of material removal, assuming a given grinding pressure, will increase markedly as the current flow is increased up to the point where there is a breakdown through the electrolyte. The mechanism of the breakdown through the electrolyte is not clearly understood. Some amount of breakdown appears to occur when the electrolyte is intact. Very marked breakdown seems to occur when the gassing rate within the electrolyte reaches a substantial level, probably reducing the total electrolytic conductive path between the grinding tool and the workpiece. But whatever the mechanism of the breakdown may be, it is important for optimum removal rate that the current supply shall be at the maximum which can be obtained without causing marked breakdown in the electrolyte. Under some conditions, particularly in ultrafine finishing operations, it may be desirable to operate at a fixed current level below that at which any breakdown occurs.

It is possible under laboratory conditions to fix all of the factors which seem to determine the maximum voltage which may be applied across the electrolytic circuit without causing breakdown. But in actual industrial use, such stability of conditions is seldom obtained. In offhand grinding the workpiece is moved by the operator toward and away from the grinding electrode. The workpiece may also be moved angularly in order to shape the surface being ground to a desired contour. The result of such movements is to produce wide and sudden changes in the resistance path through the electrolytic circuit. Even if this variability were controlled, as it is to some degree where the workpiece is held and moved mechanically, there still seems to be considerable variation, some of it occurring during the actual operation and some of it arising as the result of change from one grinding electrode to another, some of it arising from changes in electrolyte and electrolyte flow, etc.

The problem is complicated by the fact that the resistance path through the electrolyte is quite low; for example, in grinding a workpiece having a cross section of ½" square (e.g., ¼ sq. in.) the resistance path through the electrolyte from the workpiece to the grinding electrode may in a typical situation be of the order of 0.1 ohm. Any electric supply system using normal components is likely to have a resistance through the circuit components and through the connections themselves which is at least equally great and usually greater. The rate of current flow is normally quite high and may range above 100 amperes. The result is that any substantial change in the resistance through the electrolytic circuit proper will cause changes in voltage drop through the supply system components and will thus cause substantial variation in the voltage applied to the electrolytic circuit. If the voltage is properly adjusted for what might be considered a normal running condition, then if the resistance in the electrolytic circuit increases—for example, in narrowing the area of contact by shaping one of the corners—then the applied voltage will rise and cause a breakdown through the electrolyte. If, on the other hand, the operator shifts to work on a larger workpiece, the resistance in the electrolytic circuit proper decreases. Accordingly, there is a greater voltage drop through the components of the supply system, and a voltage less than the optimum will be applied across the electrolytic circuit with a consequent reduction in cutting speed.

In theory, this might be avoided by constructing a very large supply system having extremely low internal resistance, but the cost of such a system would be prohibi-

tive. It might also appear to be possible to use one or more of the constant voltage transformer devices which have been used to some extent for other applications, but most of these are either quite costly, particularly for the heavy currents here needed, or provided a less accurate control than is required.

The purpose of this invention is to provide an improved method of controlling the electrical energy supply to meet the wide variations which are encountered in practical application of electrolytic grinding and, at the same time, to permit making an apparatus which is reasonable in cost so that it can be widely used.

Another object of this invention is the provision of improved apparatus for supplying current to an electrolytic grinding system, which apparatus controls the voltage applied to the electrolytic circuit and which overrides the voltage control to control the current supply in response only to high frequency components generated as the result of sparking or arcing in the electrolytic circuit between the workpiece and the grinding electrode; an indication of some degree of electrolytic breakdown.

Another object is the provision of apparatus which will hold the voltage at which current is supplied to an electrolytic grinding system within adjustably close limits.

Another object is the provision of apparatus which will hold the voltage and current supplied to an electrolytic grinding system at an adjustably fixed level until such time as sparking or arcing may occur between the workpiece and the grinding electrode, at which time the applied voltage will automatically be reduced.

In the drawings:

FIG. 1 is a schematic darwing of an electrolytic grinding apparatus with a circuit diagram of a form of the control apparatus of this invention in which control of the voltage applied to the electrolytic grinding system is responsive to high frequency components caused by sparking or arcing between a workpiece and a grinding electrode;

FIG. 2 is a circuit diagram of a variant of the control apparatus of FIG. 1. In FIG. 2 thyratron tubes are used instead of saturable reactors in order to achieve the desired control;

FIG. 3 is a fragmentary circuit diagram showing the use of plasmatron tubes instead of thyratron tubes as the control elements; and

FIG. 4 is a circuit diagram of apparatus in which the applied voltage is controlled both in an absolute sense and in response to sparking or arcing between a workpiece and an electrolytic grinding electrode.

Referring to FIG. 1, any more or less standard grinding machine may be used when adapted for electrolytic grinding. It may consist of a driving motor **12** having a spindle **11** and a grinding electrode **10** mounted through insulating member **13** on the spindle. The grinding electrode will preferably consist of a single layer, diamond bearing grinding wheel made in accordance with Keeleric Patent No. 2,368,472 for "Method of Making Abrasive Articles," issued January 30, 1945. The diamond particles will preferably protrude .001" or .002" from the metallic surface of the electrode, although greater or less spacing may also be used satisfactorily. The upper limit of the spacing is determined partly by loss of efficiency through passage of current through a greater thickness of electrolyte and partly also by cost factors and other difficulties inherent in using the larger size particles. As a practical matter, a protrusion of about .010" is near the upper limit. The lower limit is controlled by the necessity for an adequate supply of electrolyte between the workpiece and the metal surface of the grinding electrode. A protrusion of about .0005" seems to be the lower limit for satisfactory operation.

Means are provided for connecting the negative side of the direct current supply to the grinding electrode through a brush **32** held by spring **33**, which in turn is mounted on insulating pedestal **34** fixed to the bed **14** of the machine.

A tool pedestal **15** is provided and the positive side of the direct current supply is connected to this pedestal through bed **14**. The workpiece **17**, which may be made of a sintered carbide sometimes bound by cobalt or similar material, is held manually or otherwise on the pedestal **15**. A nozzle **23** and supply conduit **22** are provided for feeding electrolyte to the work area. The nozzle is preferably directed near the center of the wheel, so that the motion of the wheel causes a film of electrolyte to spread evenly over its surface. This is of use in preventing pile-up of electrolyte against the leading side of the tool, which tends to cause unwanted electrolytic action on the side of the tool, thus making it difficult to obtain a sharp and clean edge. The pump **21** for supplying electrolyte to the conduit is conventional, and so is the shroud **24** to collect the splatter from the wheel and the return system **25** and sump **20**. All of these components are like those used for conventional wet grinding.

Turning now to the electrical supply and control system, there is provided a tapped line transformer **82** intended to accommodate a variety of available line voltages without the need for a variety of internal circuit components. As shown here, a three phase system is employed, but it will readily be seen that the same system may be applied to a single phase or two phase system by adaptation which will be readily understood. In the supply lines leading from line transformer **82** there are provided saturable, iron core reactance coils **84**. The main windings have low resistance, and, when their iron cores are saturated, pass the line voltage with little loss. The cores are saturated to greater or less degree by bias windings **86**, the bias level being adjustable by potentiameter **122**. The current is then passed through voltage reducing transformer **90** and through the rectifier system comprising rectifier elements **92** to the electrolytic circuit proper, which consists of supply lines **94**, brush **32**, movable grinding electrode **10**, the electrolyte, the workpiece **17** and the tool pedestal **15**.

In one of the supply lines **94** a shunt resistor **96** is provided across which the control signal is generated.

This control signal is fed to transformer **98** connected in shunt with resistor **96** and then amplified by triode V–1*a*. Thus, the resistor **96** and/or the primary of transformer **98** comprise an impedance arrangement connected in series with the load for sensing voltage changes thereacross.

The output of triode V–1*a* is connected through a cathode follower tube V–1*b* to a high pass filter comprising inductance **104**, condensers **106** and **108**, and resistor **110**. The components of this filter are designed to provide sharp attenuation below 1500 cycles per second and minimum attenuation above this frequency. This is done in order that alternating current supply ripple in the electrolytic circuit will not have effect on the control apparatus.

In this application the term "high frequency" is used to indicate the alternating current components which arise from sparking or arcing in the electrolytic circuit, and the term "low frequency" is used to designate alternating-current components which arise from ripple in the supply source, whatever it may be. This distinction is made because in other contexts, as in the communications art, these terms sometimes are given meanings different from the meanings intended here.

The filtered signal is then passed through transformer **112**, germanium rectifier **114**, and is partially integrated by condenser **116** and fed from potentiometer **118** to the control grid of pentode V–2. Potentiometer **118** adjusts the gain or sensitivity of the control system. This adjustment will be set to cause operation near the critical voltage of the electrolytic circuit as hereinafter explained.

When adjusted at the minimum sparking level, the

finish achieved may be as fine, when measured by a Brush analyzer, as five micro-inches R.M.S.

The output of pentode V–2 is connected to control windings 85 which augment the flux produced by bias windings 86. Normally, the output of pentode V–2 is sufficient to energize control windings 85 to such an extent that a substantial degree of saturation of the iron cores of reactance coils 84 exists. In response to an arcing signal, the output of pentode V–2 is reduced, thereby reducing the degree of saturation of the iron cores of reactance coils 84. Under these conditions the effective inductance increases and the current passed is reduced. The level to which the current falls may be set by the adjustment of potentiometer 122 which controls current supply to bias windings 86. The lower the current supplied to bias windings 86, the lower will be the minimum saturation of iron cores of reactance coils 84, and, accordingly, the lower the current will be dropped in response to signal generated by oscillations caused by sparking or arcing.

The electric supply system for the control elements just described is a conventional half-wave rectifier system with a voltage doubler circuit for B supply for pentode V–2. It consists of transformer 124, rectifiers 126 and 128, and condensers 130, 132 and 134.

Turning to FIG. 2, there is shown an alternative control system in which thyratron tubes are used in lieu of reactance coils as a means of controlling the input to the transformer and rectifier circuit.

As in the system of FIG. 1, a signal is taken from one of the main direct current leads 94. This may be done by use of a resistor 96 and a transformer as in FIG. 1, or it may be accomplished by use of a doughnut coil 201 around one of the leads 94. The signal is then filtered through a high pass filter for the purpose of eliminating low frequency components (usually 60-cycle or 180-cycle ripple). The signal may then be passed through a gating circuit by which highly transient signals are rejected. Thus, an occasional spark—as, for example, that which is created when contact is first made between the workpiece and the grinding electrode—is rejected and only a more or less continuous signal is passed. The signal is then amplified and fed to two transformers 203, each having two secondaries. Detectors 205, which may be germanium rectifiers, feed the signal from the secondaries of the transformers to potentiometers 207. Condensers 209 are connected across the output of each rectifier circuit in order to give some smoothing to the output signal. Potentiometers 207 serve to adjust the control point. The rectified signals are then fed to the grids of thyratron tubes *Th*–1, *Th*–2, *Th*–3, and *Th*–4, connected in the conventional and well known manner in two of the three legs of the three phase, alternating current supply system, the components of which, together with the rectifier system, are otherwise like those of FIG. 1.

In response to a signal resulting from sparking or arcing at a predetermined level, the control grids of the thyratrons are rendered more negative with respect to the thyratron cathodes, and thus the firing point is raised so that a lesser amount of each cycle is passed by the thyratrons to the transformer 90. The output of transformer 90 is rectified by rectifiers 92 and fed to the electrolytic grinding system through leads 94.

While there may be some advantage in a pulsing system, this is not entirely achieved by the thyratron system and there is some tendency to introduce transient peak voltages which under some conditions is undesirable. This may be overcome by the use of a relatively new type tube called a "plasmatron."

In FIG. 3 there is shown a circuit in which "plasmatrons" are substituted for the thyratrons. The diagram is fragmentary and illustrates how two plasmatrons *Pl*–1 and *Pl*–2 are to be substituted for thyratrons *Th*–1 and *Th*–2 of FIG. 2. It will be understood that the third leg of the three-phase, alternating current supply is to be connected through two more plasmatrons, just as two more thyratrons are used in the third leg in FIG. 2. The remainder of the circuit may be like that of FIG. 2.

The plasmatron is currently produced by Bendix Aviation Corporation and is described in its publication No. R33–3, the tube itself being identified as "Red Bank Type RXB–103005." The tube is a gas filled type in which, however, a smooth and gradual control of the resistance of the tube is achieved by the counterpart of a grid in an ordinary vacuum tube or thyratron. This control element is designated a garrote, and is here designated *g*. As applied in this system, the advantage of the plasmatron is that the current supply is controlled not by limiting the duration of each cycle or pulse, as in the case of the thyratron, but by introducing a controllable resistance into the circuit, thus producing a smooth regulation of the total current passed. The presently available plasmatron tubes are low in capacity, and, accordingly, it is necessary to use a plurality of the tubes in parallel, the number required being dependent upon the size of the electrolytic grinding installation.

In the drawing, transformer secondaries 203 of FIG. 2 are designated 203–S. Other similar components carry similar reference numerals. Batteries C are provided for bias.

The three systems just described and shown in FIGS. 1, 2, and 3 have the advantage of reasonable simplicity but leave open one problem. When the workpiece is not in contact with the grinding electrode the voltage will rise to the maximum which the system is capable of delivering. This voltage is, of course, determined by the constants of the transformer circuits, etc. This no-load voltage will be somewhat higher than the electrolytic circuit will normally use. The no-load voltage will be reduced during actual operation, partly by voltage drop through the various resistances inherent in the supply circuit and partly through operation of the automatic control system in response to sparking and arcing. However, upon first advancing the workpiece toward the grinding electrode there is likely to be a substantial amount of sparking and arcing resulting from the energy stored in the inductances of the circuit. The control system does not respond quite instantaneously, and the result may be to cause some damage to the grinding electrode and some roughness on the surface of the workpiece being shaped. Quite apart from this, the initial flash may be disturbing to operators, particularly those who have not had previous experience with this type of equipment.

This difficulty is of less consequence when the size of the workpiece is somewhere near the top limit for which the system is designed. That is, the initial sparking and arcing will not be of any serious consequence if the size of the workpiece is sufficient to establish an electrolytic path capable of using somewhere nearly all of the full output of which the supply system is capable. But in some instances it is desired to be able to grind workpieces of widely different sizes, and the problem of initial sparking becomes quite troublesome if the cross-sectional area of the workpiece is reduced to, say, ¼ of the maximum area for which the system is designed. Such a change in area occurs, for example, in changing from a tool bit approximately ½" square to one which is ¼" square, and of course any shift from full face grinding to the grinding of a corner will cause even more marked variations.

This latter variation, which occurs when a corner is ground, is often, if not primarily, due to the tendency of the diamond abrasive to "bite" into the workpiece when the area of contact is reduced while the force urging the workpiece toward the abrasive remains substantially constant. Often, the workpiece makes point or line contact with the abrasive to exaggerate the problem.

This tendency of the diamond to bite into the workpiece will change the spacing between the workpiece and the conductive face of the grinding wheel. A change in

this spacing effects a corresponding change in the critical voltage at which arcing and/or sparking will occur.

Changes in this critical spacing also occur as a result of applying forces of differing intensity to the workpiece when urging it toward engagement with the grinding wheel, as a result of wear on the abrasive over extended periods of use, and as a result of the differing spacing characteristics of differing grinding wheels.

To permit easy accommodation of a wide range of sizes in the workpieces and wide variations in the spacing between the workpiece and the conductive face of the grinding wheel, the system shown in FIG. 4 is provided. The gist of the system of FIG. 4 is that it provides both a constant voltage control and, in addition, a spark or arc responsive control. It is the combination of these features to which the present invention is directed.

As in the other systems, a high frequency signal is taken from one of the direct current leads 94 across a resistor 96. The signal is taken through condenser C–1 through transformer T–1, and is amplified by triode V–1*a* and connected through a cathode follower V–1*b*, as in FIG. 1. The amplified signal is passed through resistor R–8 to a high pass filter consisting of condensers C–5 and C–6 and inductance T–2. The high pass filter is used to eliminate unwanted low frequency components not caused by sparking or arcing. The amplified and filtered signal is then passed through transformer T–3, and is rectified and partially integrated by the components comprising rectifier D–4, condenser C–4, and potentiometer R–9.

This much of the system serves to provide a direct current signal responsive to and proportional to the sparking or arcing which may exist between the workpiece and the grinding electrode.

The next portion of the system consists of a voltage balance and bias system, the purpose of which is to provide a signal for controlling the direct current voltage impressed across the electrolytic circuit between the workpiece and the grinding electrode. The balancing system consists of the following components: One of the two secondaries of transformer T–4, two rectifier units D–2 and D–3, condensers C–9 and C–10, and potentiometer R–11. These components generate a direct current which is connected so as to balance out the voltage of the direct current across supply lines 94. Note that connections are made to lines 94 for the purpose of getting a direct current signal at this point. These connections should be close enough to the actual electrolytic circuit so that there is virtually no voltage drop between the point of connection and the electrolytic circuit itself.

The level at which the balance is to be obtained and at which control will be held may be adjusted by potentiometer R–11. As this balance voltage is reached the control system tends to hold the voltage at this level.

A bias voltage is obtained from the following components: a second secondary of transformer T–4, rectifier D–1, condenser C–8, and potentiometer R–10. This bias voltage, which is adjustable through potentiometer R–10, sets the sensitivity of response of the control system to changes in voltage and may be readjusted depending upon the level at which voltage control is to occur.

Potentiometer R–9 controls the amount or rate of response of the control system to sparking and arcing.

By examining the circuit, it will be seen that the direct current signal derived from high frequency components and amplified, filtered, and rectified is, in effect, set in series with the signal derived from the direct current voltage balance and bias system. Thus, the two control signals are additive. If the direct current voltage rises above the predetermined balance level, a direct current signal is fed to the power amplifier, tending to reduce the supply voltage. Or if there is sparking or arcing above a predetermined level, a similar signal is delivered to the power amplifier. Or if both occur together—that is, if the supply voltage rises and if concurrently there is sparking or arcing—a combined signal will be delivered to the power amplifier to reduce the voltage and, thus, concurrently to reduce the sparking or arcing. Of course, the spark derived signal must be amplified so that its magnitude is sufficient to override any tendency of the voltage derived signal to increase the output voltage when it is being lowered in response to the control effect of the spark derived signal.

The power amplifier is conventional. It includes a power tube V–2, a fixed voltage bias tube V–3, and three pentode tubes V–4 connected in parallel. The power transformer T–4*a* may be, and usually is, made integrally with transformer T–4, and the primaries of both may be common. The output of the power amplifier is fed to the control windings CW of three saturable core reactors L–1, L–2, and L–3 in series with the three legs of a three phase, alternating current supply. The greater the signal delivered to the control windings of the three saturable core reactors, the less effective they will be as inductances and the more current they will pass. Thus, the limitation of current is achieved by reducing the amount of current passing through these three control windings. Maximum current will be delivered to these windings GW when the maximum supply voltage to the electrolytic system is desired.

The three phase alternating current thus controlled by the saturable core reactors is fed to a transformer and rectifier in the conventional manner (as illustrated, for example, in FIGS. 1 and 2), and thence to direct current supply lines 94.

The use of this invention permits maximum electrolytic material removal at all times. Without it, if the voltage be initially established at a proper level, then as the electrical load through the electrolytic circuit between the workpiece and the grinding electrode increases, the supply voltage will fall due to increased resistance drop in the supply system. Or if the voltage be properly set for full load conditions, it will rise under reduced load (as in shaping a corner) and cause excessive sparking and arcing. This latter operation may be harmful to the grinding electrode, and will produce a rough finish on the workpiece.

It has been found that with any given grinding electrode, electrolyte, speed of grinding electrode, etc., a critical voltage range exists from the point when the electrolyte begins to break down up to the point where substantially all of the current is carried by arcing. Below this critical range electrical removal of material is electrolytic. Above it, the electrical material removal is caused primarily by electro-erosion—e.g., arcing—with all of its attendant problems.

Sometimes it is observed that within the critical range of voltage, the material removal rate may actually decline with increased voltage. It may be that as the electrolyte breaks down and heavy sparking begins, the electrolytic action is impaired by puncturing and dispersion of electrolyte. Yet the sparking is not heavy enough to bring about sufficient electro-erosion to offset the loss of electrolytic effectiveness. The voltage level just below this point is here referred to as the critical voltage and represents the ideal level for operation according to this invention. This critical voltage seems to be independent of the size of the workpiece or of the size of the area of the workpiece which is being ground. This general observation will hold true over a substantial range of sizes, although some deviation from the general rule may occur to the extent that the size of the workpiece being ground may have a secondary effect on the rate of flow of electrolyte between the grinding electrode and the workpiece, but the general statement holds over a sufficient range of sizes so that once the critical voltage is established for a given grinding electrode running at a given speed and supplied with a given electrolyte at a given flow rate, then workpieces of different size may be shaped and different surface areas may be presented to the grinding electrode as the workpiece is moved without requir-

ing any marked change in the direct current supply, provided only that the voltage of the supply system is held substantially constant at or slightly below the critical voltage.

With a diamond bearing grinding electrode in which the diamond particles protrude approximately .001" it has been found that the critical voltage, with an electrolyte substantially like that disclosed in the aforementioned Keeleric copending application, will be around 8 volts. If the protrusion of the particles is about .005", then the critical voltage will be around 24 volts. As the grinding electrodes are worn so that the protrusion distance is reduced, then the critical voltage will be reduced. This critical voltage will vary somewhat with different electrolytes, different flow rates of electrolyte and different speeds of the grinding electrode.

The system of FIG. 4 will hold the voltage constant within about 2%, which is an adequate control for this purpose. Since it may not be possible in industrial practice to set the fixed voltage at precisely the critical level, the voltage may be set slightly higher than the critical voltage, placing reliance upon the spark-generated signal to reduce the voltage to the desired level. Thus, for example, if the critical voltage is 10.1 volts in a given setup, the electrical system might be set for 10.5 volts or 11 volts, and the spark responsive portion of the control will then bring about the further reduction which is needed. Voltmeter V will be helpful in this initial adjustment.

One advantage of this system is that the voltage will not rise to excessive levels under the no-load condition when the workpiece is not against the grinding electrode. When the workpiece is removed from the grinding electrode for inspection or measurement, the direct-current voltage in the supply lines 94 will tend to rise, but the control system will overcome this tendency. If it is found that there is excessive initial sparking, this indicates that the voltage has been set too high and should be adjusted to a lower value. Attention should be directed here to load resistor 97 across the lines 94. This resistor applies at all times a minimum load to cause a sufficient amount of current to be flowing in control reactors L–1, L–2, and L–3 as to permit their being effective for control purposes during the time when the workpiece is not in contact with the grinding electrode. The value of the resistor is higher than the normal resistance of the electrolytic circuit itself, and it absorbs only a very small part of the total energy supplied when grinding operations are going on.

By use of the control system of this invention it has been found possible to achieve removal rates very much greater than those actually obtained in service operations where supply systems are used which do not have the automatic control features of this invention. The increase of the removal rate is accomplished primarily by enhancement of the electrolytic action rather than by increased grinding pressure. Thus, there is not only a very marked saving in labor through acceleration of the shaping operation, but there is, in addition, a saving in the use rate of the expensive abrasive tools. Accordingly, the added cost of the electronic control components is more than offset by the great economies in operation.

While a preferred embodiment of this invention has been shown and described, it will be apparent that numerous modifications and variations thereof may be made without departing from underlying principles of the invention. It is therefore desired by the following claims to include within the scope of the invention those variations and modifications which may be obtained through the use of substantially the same or equivalent means.

What I claim as new and desire to secure by Letters Patent is:

1. In an electrolytic grinding system having an electrolytic circuit and a direct current supply circuit therefor, said supply circuit having internal resistance, automatic means for preventing substantial rise in voltage of said direct current supply circuit under conditions of reduced load in said electrolytic circuit, second automatic means comprising an impedance arrangement connected in series with the electrolyte in said electrolytic circuit and said workpiece and electrode for sensing resistance changes across the electrolyte, and means controlled responsive to said sensed changes and coupled to said first automatic means for reducing the voltage of said direct current supply circuit in response to sparking in said electrolytic circuit.

2. In combination, a direct current supply system for an electrolytic grinding circuit having an alternating current input, automatic means acting on said alternating current input normally holding the direct current output voltage applied to the electrolytic grinding circuit constant, means having its output coupled to said automatic means for automatically reducing the direct current output voltage in response to sparking in the electrolytic grinding circuit including signal producing means connected in series with the electrolyte in said electrolytic grinding circuit and said workpiece and electrode responsive to alternating current components in the electrolytic grinding circuit, and means for discriminating against low frequency, alternating current components not arising from the electrolytic circuit.

3. Electrolytic grinding apparatus including an electrolytic load circuit and a high current, low voltage, direct current supply system, said direct current supply having an alternating current input and a rectifier, a voltage control system in said direct current supply system including means connected in series with the electrolyte in said electrolytic load circuit and said workpiece and electrode and responsive to the direct current voltage appearing across the electrolytic load circuit and acting on said alternating current supply adapted to maintain a substantially constant direct current voltage output under widely varying load conditions and including means responsive to alternating current components arising in the electrolytic load circuit and coupled to said means responsive to said direct current voltage across the electrolytic load circuit to modulate and overrule the otherwise substantially constant direct current, whereby the direct current voltage across the electrolytic load circuit is automatically reduced in response to alternating current components arising in the electrolytic load circuit.

4. Apparatus as defined in claim 3 in which the means responsive to the direct current voltage across the electrolytic load circuit includes adjusting means to adjust and establish the voltage at which a direct current is normally regulated.

5. Apparatus as defined in claim 3 in which the means responsive to alternating current components arising in the electrolytic load circuit includes adjusting means to adjust the rate of response to said alternating current components.

6. Apparatus as defined in claim 3 in which the means responsive to the direct current voltage across the electrolytic load circuit includes adjusting means to adjust and establish the voltage at which a direct current is normally regulated, and in which the means responsive to alternating current components arising in the electrolytic load circuit includes adjusting means to adjust the rate of response to said alternating current components.

7. Electrolytic grinding apparatus including an electrode adapted for relative motion with respect to a workpiece and having abrasive particles protruding therefrom to prevent direct short circuiting between the electrode and the workpiece, and means for holding the workpiece in working relationship against the abrasive particles on the electrode, means for flowing an electrolyte between the electrode and the workpiece and a direct current supply system connected to the electrode and the workpiece in a sense to make the workpiece an anode, thereby es-

tablishing an electrolytic load circuit between the electrode and the workpiece, said direct current supply system including a source of alternating current and a rectifier, electric control means interposed between said alternating current source and said rectifier, automatic means comprising an impedance element connected in series with said electrolytic load circuit and said workpiece and electrode for sensing voltage changes in said load circuit and responsive to direct current appearing across said electrolytic load circuit and acting on said alternating current source to maintain substantially constant direct current voltage over widely varying load conditions, and means responsive to alternating current components generated in said electrolytic load circuit and having its output coupled to said automatic means to reduce the normal regulated direct current voltage appearing across said electrolytic load circuit whenever alternating current components are generated therein.

8. Apparatus as defined in claim 7, in which adjusting means are provided for adjusting the direct current voltage at which regulation normally occurs.

9. Apparatus as defined in claim 7, in which adjusting means are provided for adjusting the rate of response to alternating currents generated in the electrolytic load circuit.

10. Apparatus as defined in claim 7, in which adjusting means are provided for adjusting the direct current voltage at which regulation normally occurs and in which adjusting means are provided for adjusting the rate of response to alternating currents generated in the electrolytic load circuit.

11. In electrolytic grinding apparatus a rotating electroconductive electrode having insulating abrasive particles protruding from a working face thereof, means for holding a workpiece in working relationship against the protruding abrasive particles on the electrode, means for flowing an electrolyte between the electrode and the workpiece, direct current supply means connected to the electrode and the workpiece in a sense to make the workpiece an anode, said direct current supply means including an alternating current source and a rectifier, at least one saturable core reactor interposed between the alternating current source and the rectifier and having a direct current control coil adapted to be energized by a variable direct current, electronic means having a direct current output connected to said control coil and including connections to the direct current output of the rectifier, means comprising an impedance element connected in series with said electrode and workpiece to sense resistance changes occurring thereacross for establishing an adjustable reference voltage, circuit means for deriving a signal from the difference between the reference voltage and the output voltage of the rectifier, means for conducting the signal to an amplifier, and means connecting the amplifier to the control coil of the saturable core reactor, and adjustable potentiometer means adapted and connected to permit substantially continuously variable adjustment of the level of the reference voltage.

12. In equipment of the type in which a hard conductive workpiece and a movable electrode are brought into close proximity, in which an electrolyte is introduced between the workpiece and electrode, and in which an alternating current supply is rectified to apply a direct current potential across the workpiece and electrode for electrolytic grinding of the workpiece, the combination with the supply of signal responsive apparatus controlling the value of the applied potential, a first circuit means including a linear circuit element connected in series with said electrode and workpiece and responsive to changes in applied potential for producing first signals as a function of change in applied potential from a reference potential, a second circuit means responsive to high frequency signals produced by arcing and sparking between the electrode and workpiece producing second signals as a function of the high frequency signals, and circuit means applying the first signals to the apparatus in a manner tending to maintain a substantially constant applied potential and applying the second signals to the apparatus reducing the applied potential to inhibit substantial arcing and sparking.

13. In equipment of the type in which a hard conductive workpiece engages a movable electrode having a conductive workface and abrasive particles projecting from the workface not substantially more than .010", in which an electrolyte is introduced between the workface and workpiece, and in which an alternating current supply is rectified to apply a direct current potential across the workpiece and electrode for grinding of the workpiece by abrasion and electrolysis, the combination with the supply of signal responsive apparatus controlling the value of the applied potential, a first circuit means including a circuit element connected in series with said electrode and workpiece and responsive to changes in applied potential for producing first signals as a function of change in applied potential from a reference potential, a second circuit means responsive to high frequency signals produced by arcing and sparking between the electrode and workpiece producing second signals as a function of the high frequency signals, and circuit means applying the first signals to the apparatus in a manner tending to maintain a substantially constant applied potential and applying the second signals to the apparatus in a manner reducing the applied potential to inhibit substantial arcing and sparking.

14. In equipment of the type in which a hard conductive workpiece and a movable electrode are brought into close proximity, in which an electrolyte is introduced between the workpiece and electrode, and in which an alternating current supply is rectified to apply a direct current potential across the workpiece and electrode for electrolytic grinding of the workpiece, the combination with the supply of signal responsive apparatus controlling the value of the applied potential, a first circuit means including a circuit element connected in series with said electrode and workpiece and responsive to changes in applied potential for producing first signals as a function of change in applied potential from a reference potential, a second circuit means responsive to high frequency signals produced by arcing and sparking between the electrode and workpiece producing amplified second signals of greater intensity than the first signals as a function of the high frequency signals, and circuit means applying the first signals to the apparatus in a manner tending to maintain a substantially constant applied potential and applying the second signals to the apparatus in a manner reducing the applied potential to inhibit substantial arcing and sparking.

15. In equipment of the type in which a hard conductive workpiece and a movable electrode are brought into close proximity, in which an electrolyte is introduced between the workpiece and electrode, and in which an alternating current supply is rectified to apply a direct current potential across the workpiece and electrode for electrolytic grinding of the workpiece, the combination with the supply of signal responsive apparatus controlling the value of the applied potential, an adjustable first circuit means including a circuit element connected in series with said electrode and workpiece and responsive to changes in applied potential for producing first signals as a function of change in applied potential from a reference potential which produces at least sparking between the electrode and workpiece, an adjustable second circuit means responsive to high frequency signals produced by arcing and sparking between the electrode and workpiece producing second signals as a function of the high frequency signals, and circuit means applying the first signals to the apparatus in a manner tending to maintain the applied potential substantially at the reference level and applying the second signals to the apparatus in a

manner reducing the applied potential to inhibit substantial arcing and sparking.

16. In equipment of the type in which a hard conductive workpiece and a movable electrode are brought into close proximity, in which an electrolyte is passed between the workpiece and electrode, and in which an alternating current supply is rectified to apply a direct current potential across the workpiece and electrode for electrolytic grinding of the workpiece, the combination with the supply of applied potential control apparatus consisting essentially of signal responsive means controlling the value of the applied potential, a first circuit means including a circuit element connected in series with said electrode and workpiece and responsive to changes in applied potential for producing first signals as a function of change in applied potential from a reference potential, a second circuit means responsive to high frequency signals produced by arcing and sparking between the electrode and workpiece producing second signals as a function of the high frequency signals, and circuit means applying the first signals to the signal responsive means tending to maintain a substantially constant applied potential and applying the second signals to the signal responsive means in a manner reducing the applied potential to inhibit substantial arcing and sparking.

17. An arrangement for controlling the potential applied between a grinding wheel and a workpiece which are in close proximity and between which an electrolytic solution is passed for carrying current between said wheel and workpiece, the improvement comprising an alternating current power supply, means for rectifying the current provided by said supply to provide a direct current output voltage, means for applying said direct current output voltage across said grinding wheel, electrolyte, and workpiece, and an impedance arrangement connected in series with said wheel, electrolyte, and workpiece, for sensing voltage changes appearing thereacross to provide corresponding signals for use in controlling the provided direct current voltage.

18. The arrangement claimed in claim 17, in which said impedance arrangement comprises a resistance element having a linear response to voltage changes.

19. The arrangement claimed in claim 18, including a transformer primary connected in shunt with said element for transmitting the voltage changes occurring across said element for use in controlling said direct current output voltage.

20. The arrangement claimed in claim 17, including means for controlling the output voltage only in response to voltage fluctuations having a predetermined rate of change.

21. The arrangement claimed in claim 17, including means for selecting the level at which said sensed voltage changes are effective for controlling said direct current output voltage.

22. The arrangement claimed in claim 17, including means for selecting a sensed rate of voltage change for use in controlling said direct current output voltage.

23. An arrangement for controlling the potential applied between an electrode and a workpiece which are in close proximity and between which an electrolytic solution is passed for carrying an electrical current between said electrode and workpiece for electrolytically eroding said workpiece, the improvement comprising means for sensing changes occurring in said potential between said electrode and workpiece, and means for automatically altering the potential applied between said electrode and workpiece in response to said sensed changes for maintaining the potential between said electrode and workpiece at a desired value.

24. The arrangement claimed in claim 23 in which said sensing means includes an impedance element in series with said electrode and workpiece and said automatic altering means comprises an amplifier for amplifying the character of said sensed changes, and means responsive thereto for reversing the direction of potential change by an amount dependent on the amplitude of the change.

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