Nov. 27, 1956 G. E. COMSTOCK 3D., ET AL 2,772,232

ELECTROLYTIC GRINDING APPARATUS

Filed Dec. 30, 1952 4 Sheets-Sheet 1

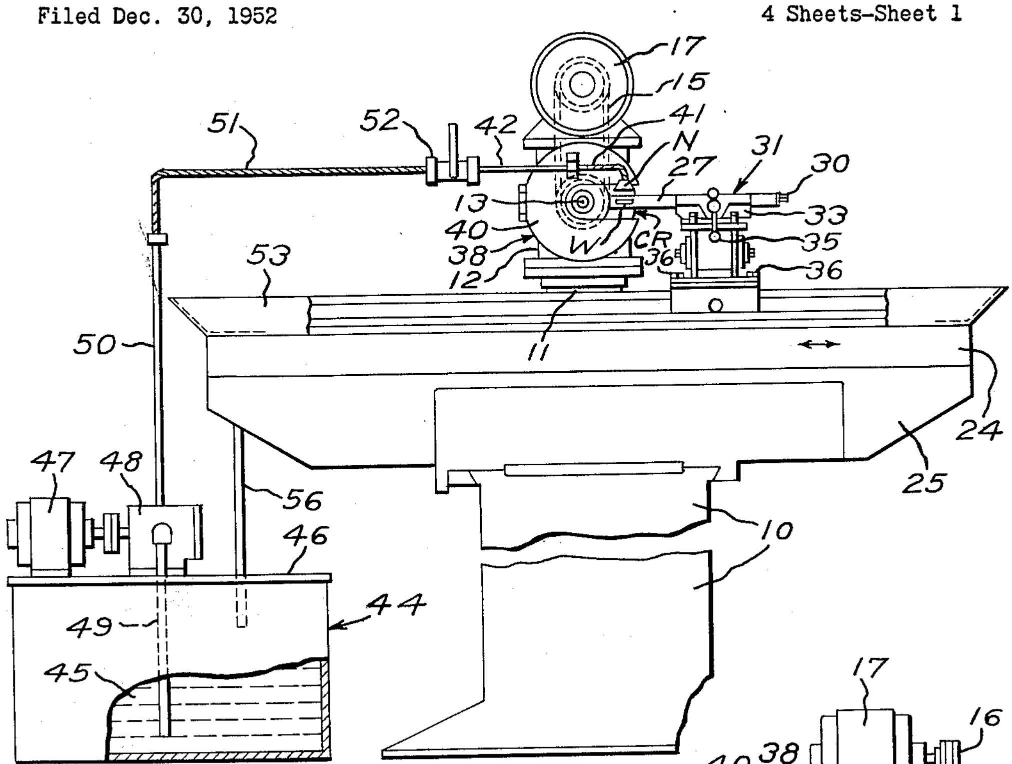

FIG. 1

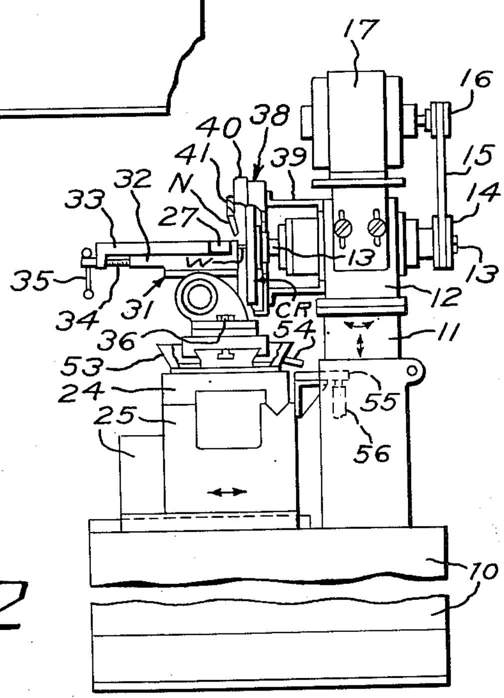

FIG. 2

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ELECTROLYTIC GRINDING APPARATUS

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FIG. 3

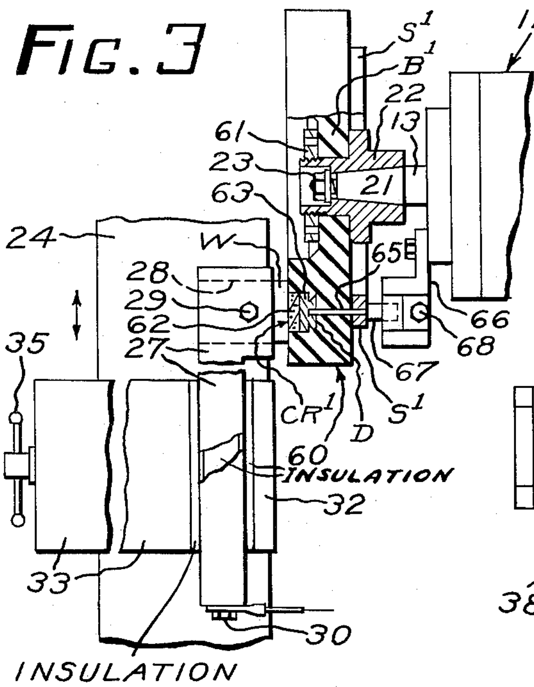
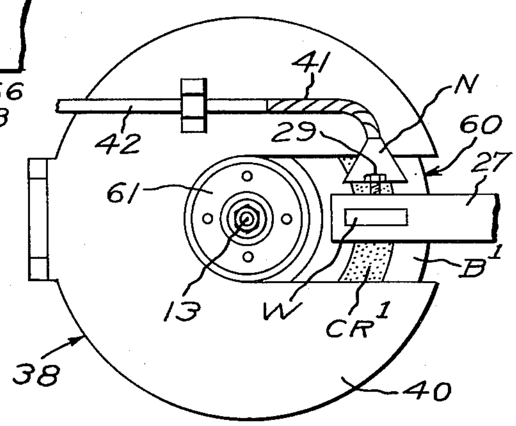


FIG. 5



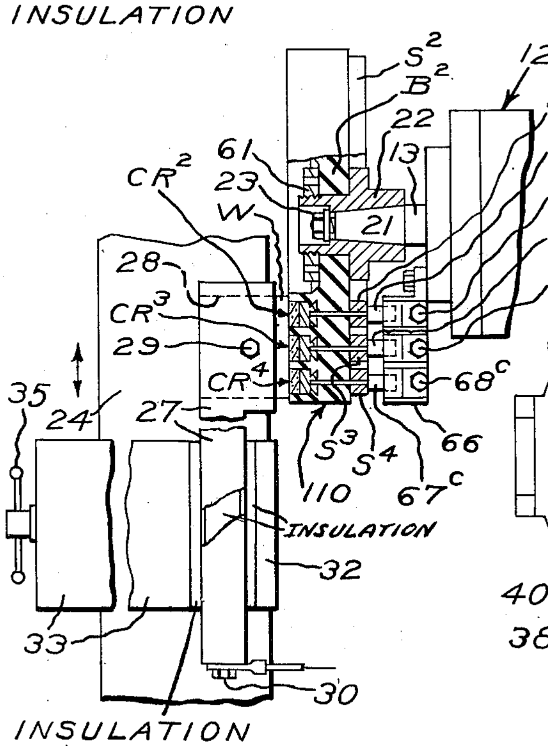
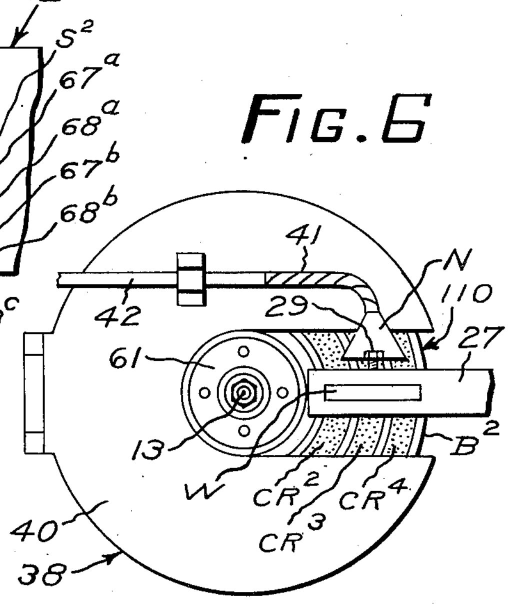


FIG. 4

FIG. 6



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ELECTROLYTIC GRINDING APPARATUS

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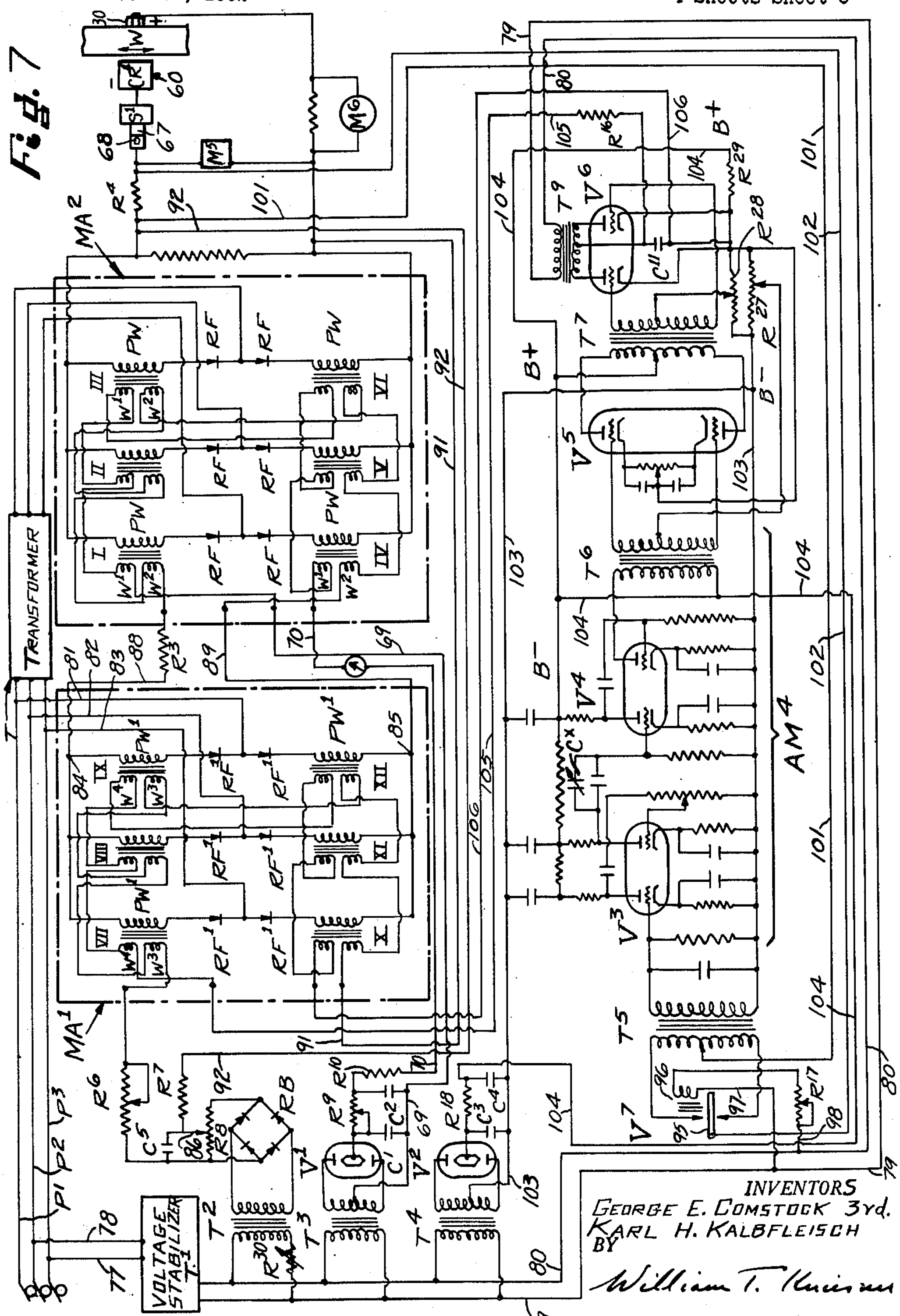

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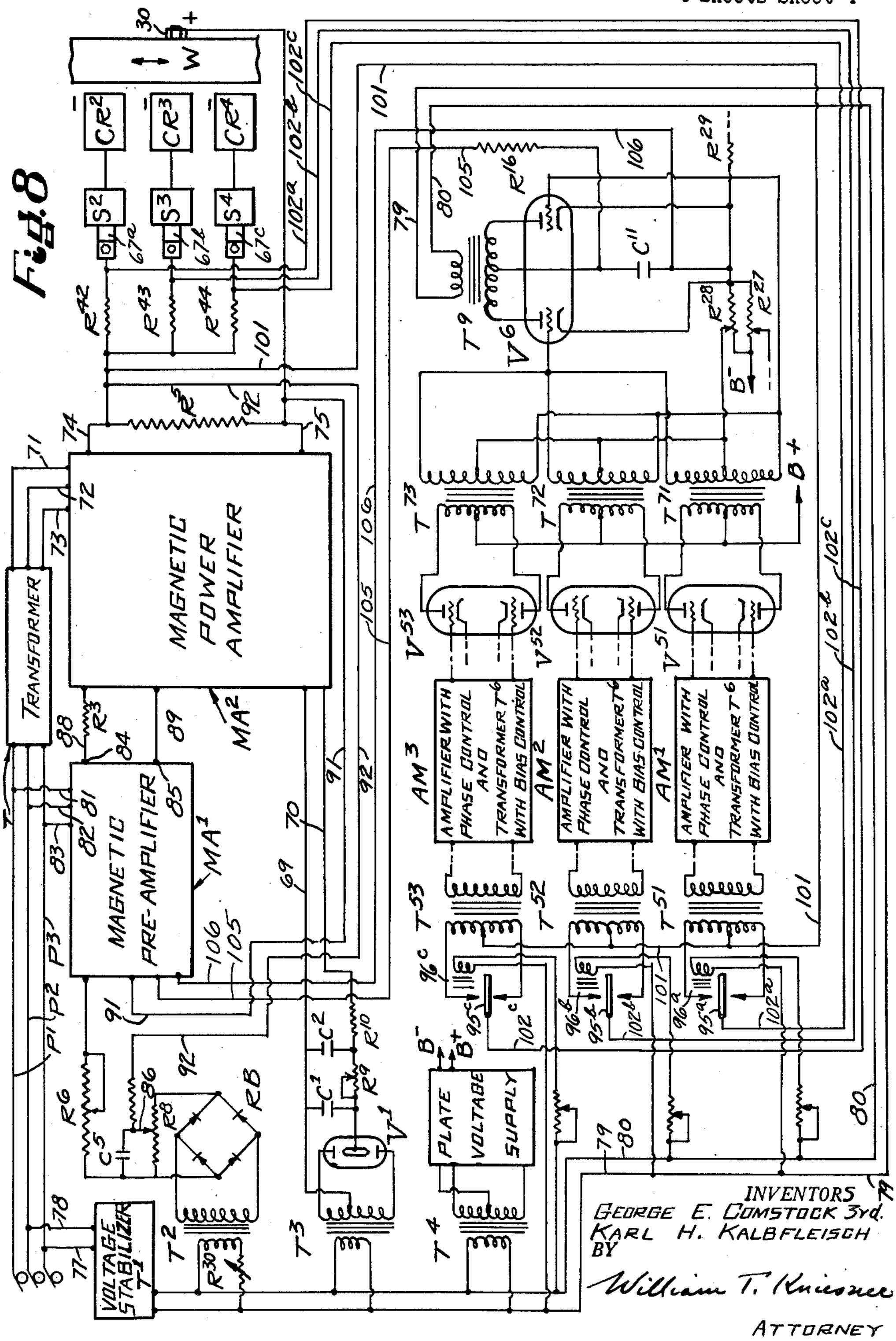
Fig. 8



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ELECTROLYTIC GRINDING APPARATUS

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Application December 30, 1952, Serial No. 328,726

13 Claims. (Cl. 204—218)

This invention relates to electrolytic grinding and the supply and control of electrical energy for effecting electrolytic stock removal from the work-piece.

One of the objects of this invention is to provide a practical and efficient system and apparatus of the above-mentioned character that will lend itself for readier and more convenient adaption to, and installation in, factories or plants already provided with circuits or sources of alternating current electrical energy, while at the same time effecting dependable and efficient controls or regulation of the electrical energy so as to materially improve stock removal capacity and achieve dependable controls against detrimental electrical actions at the locus of stock removal where the electrical energy is unidirectional or in the form of direct current. Another object is to provide an apparatus and system of the just mentioned character in which good over-all electrical efficiency may be achieved in that the conversion of alternating current electrical energy into direct current energy that is used at the locus of stock removal can be, for purposes of achieving higher stock removal capacity and avoiding detrimental arcing or current densities at the locus of electrolytic decomposition of the work-piece, controlled or regulated in response to direct current conditions at such locus. Another object is in general to provide an improved electrolytic grinding apparatus and control system therefor in which wastefulness of electrical energy or substantial heat losses of systems heretofore proposed may be dependably lessened or avoided.

Another object is to provide an electrolytic grinding apparatus and electrical energy supply and control system that will be of wide flexibility of operation and of adaptability to suit varying conditions or requirements met with in practice and yet be thoroughly dependable and superior and efficient in action. More particularly, another object is to provide such an apparatus and system, supplied from an initial alternating current source, that is readily adaptable for dependable controls at the direct current locus of electrolytic work-piece decomposition, whether the conductive "grinding" wheel consists of a single rotating conductive element or comprises a plurality of coacting rotating conductive elements capable of both individual and conjoint coaction with the electrolyte in effecting electrolytic stock removal from the work-piece.

Another object is in general to provide improved electrolytic grinding and energy supply and control systems that will be efficient, thoroughly practical, and well adapted for industrial uses and installations. Other objects will be in part obvious or in part pointed out hereinafter.

The invention accordingly consists in the features of construction, combinations of elements, arrangements of parts and in the several steps and relation and order of each of the same to one or more of the others thereof, all as will be illustratively described herein, and the scope of the application of which will be indicated in the following claims.

In the accompanying drawings, in which are shown

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illustratively the mechanical and electrical features of our invention and in which similar reference characters refer to several parts throughout the several views of the drawings,

Figure 1 is a front elevation, with certain parts shown or indicated diagrammatically, of the grinding machine;

Figure 2 is a fragmentary side elevation thereof;

Figure 3 is a fragmentary horizontal sectional view on an enlarged scale, showing certain mechanical and electrical features of one form of grinding wheel in relation to a work-holder and certain electrical features related thereto;

Figure 4 is a fragmentary horizontal sectional view on an enlarged scale, showing certain mechanical and electrical features of another form of grinding wheel in relation to a work-holder and certain electrical features related thereto;

Figure 5 is a fragmentary or detached front elevation of a wheel guard cover and associated electrolyte-distributing parts as related to the grinding wheel of Figure 3 and as seen from the front in Figure 1 and from the left in Figure 3;

Figure 6 is a fragmentary or detached front elevation of a wheel cover and associated electrolyte-distributing parts as related to the grinding wheel of Figure 4 and as seen from the front in Figure 1 and from the left in Figure 4;

Figure 7 is a diagrammatic representation of the apparatus utilizing a single rotating conductive element or ring, such as the grinding wheel of Figures 3 and 5, and of the electrical energy supply system associated therewith and of the coacting controls therefor, and

Figure 8 is a diagrammatic representation of the apparatus utilizing multiple rotating conductive elements or rings, such as the grinding wheel of Figures 4 and 6, and of the electrical energy supply system associated therewith and of the coacting controls therefor.

As conducive to a clearer understanding of certain features of our invention it may here be noted that there are many advantages to be gained in stock removal by electrolytic grinding in which, by the coaction of an electrolyte and direct or unidirectional current, stock is removed from the work-piece by electrolytic decomposition of the work face, especially for machining hard cemented carbides (such as cobalt-bonded tungsten and/or titanium carbide) whereby, when the rotating conductive element or face of the grinding wheel contains abrasive grain, the cutting action of the abrasive grain may be very materially supplemented. Most industrial plants or factories are equipped with or wired for alternating current energy, usually and illustratively three-phase and of 60 cycles. One of the objects of our invention is to provide efficient and dependable electrolytic grinding apparatus and controllable energy supply system that needs only to be electrically connected to the existing alternating current supply lines and controllably furnish, at the locus of stock removal, the required unidirectional current for electrolytic action. As heretofore attempted to be practiced, so-called electrolytic grinding has encountered various difficulties or the systems or apparatus have inherent limitations or there arise phenomena detrimental to or destructive of the grinding wheel, and these handicaps become all the more serious where, as is frequently the case, it is desirable to use diamond grinding wheels, which are costly. Another dominant aim of this invention is to avoid or alleviate such handicaps, shortcomings or risks, and to achieve materially greater over-all efficiency, whether or not diamond or other abrasives are employed, by effecting dependable and automatic controls of the conversion of the alternating current energy to direct current energy in response to changes in harmful direction of the electrical conditions at the locus of electrolytic decomposition of the work-piece.

In electrolytic grinding in which the conductive work-piece is made the anode and in which the work-wheel interface, where there may or may not be physical contact, is adequately supplied with a suitable electrolyte which also serves as a coolant, it is desirable to use high current density, since the rate of electrolytic decomposition of the work-piece face is proportional to current flow, but according to prior practices the extent to which current density can be increased to improve stock removal rate or capacity is severely limited.

For example, visible arcing or sparking can take place in the contact zone, through the electrolyte at the work-wheel interface, whether there is actual or apparent contact between the work and the wheel, and such arcing can be detrimental to the character and precision of surface which it is sought to produce on the work-piece, and it can result in high or excessive rates of wheel wear which, particularly where diamond abrasives are embodied in the wheel, can prove prohibitively costly. Moreover, even if within these limitations or handicaps means are provided for limiting maximum value of, or regulating at substantial constancy, the amperage in the circuit that includes the interface so that current of allowable and limited or regulated over-all value is uniformly distributed throughout the interface area, any operating condition that thereafter arises, such as reduction in the interface area, to cause the current density to exceed the critical value, brings about destructive arcing. Illustratively, such a reduction in area at work-wheel interface can take place upon relative traversing movement between the wheel face and the work in excess of that required for complete mutual overlap of one relative to the other. Also, the contact area can be reduced to zero upon such relative movement as to run the work-piece completely off the edge of the wheel face (or vice versa), or as would otherwise effect complete separation between the two. Furthermore, a wide variety of changes in area of the work-wheel interface, with or without physical contact, can take placed in so-called "off-hand" grinding, as when machining or shaping a cemented carbide tool by hand, as when the operator manually shifts the tool carrier on the grinder bed or table according as curved or flat surfaces have to be ground in the tool, and in such cases rapid and sometimes severe changes in actual pressure of contact between work and wheel face can come into play and thus further complicate and aggravate conditions for detrimental or destructive current densities and arcing.

Then again, detrimental arcing may also occur even when the apparent contact area is a large fraction of the maximum possible contact area, if the total current is above what may be termed the critical arcing current for given conditions; apparently small discontinuities in the surface or face tend to cause current concentrations in areas much smaller than the interface or apparent contact area, produce local heating and leading to the formation of destructive arcs, and in such case the total current, even though limited in maximum value or regulated for substantial constancy, in effect funnels through the small arcing area.

It is accordingly another dominant object of this invention to provide for reliable, economical and efficient control or regulation against such detrimental or undesirable actions and effects as those under the above, and more particularly, to so interrelating, electrically, the electrolytic cell that is active at the work-wheel interface with the direct-current producing or supplying means that the conditions existing in the former control or regulate the energy output of the latter to maintain operationally safe decomposition at the work-face at high or efficient levels.

In describing our invention we prefer to do so in connection with an electrolytic grinding apparatus in which the "grinding" wheel, while conductive, also contains abrasive grains and also because certain protective actions which the system of our invention achieves serve also to excellent advantage where both electrolytic and abrasive action take place conjointly, as is frequently desirable in practice. Any suitable mechanism or arrangement may be employed for mounting and driving the conductive grinding wheel and for mounting or supporting, or even for resting thereon for manual movement (as in so-called "off-hand" grinding), a work-piece, such as a cemented carbide tool or other piece of work or object to be ground or machined, whereby to obtain relative movements between the grinding wheel and the supported work. Many and various forms of mechanism are well known for cooperatively relating a grinding wheel and a work-piece for relative movement therebetween and providing for various relative adjustments and/or movements between the grinding wheel spindle and the work together with various manual or automatic controls for such adjustments and movements. For example, we may utilize a machine such as is shown in U. S. Patent 2,101,781, in which a work-table, underlying an adjustably mounted and rotatively driven grinding wheel spindle, is movable and reciprocable relative to the grinding wheel and is mounted on a cross slide for shifting it transversely, that is, forwardly or rearwardly of the machine, relative to the grinding wheel; in the machine of that patent the work-table can be reciprocated upon the transverse or cross slide by manual means or by fluid pressure mechanism as there described, while the cross slide may be manually or mechanically moved to advance the work-table and the work-piece supported by it in steps or at a rate according to the setting of the infeed mechanism or according to the manual actuation thereof, as by a hand wheel. Or, we may utilize a grinding machine, by way of further illustration, of the type or kind disclosed in Patent 2,381,034, the machine of that patent being particularly adapted for shaping tool bits, particularly bits or tools of the above mentioned hard cemented carbides, and in that machine the operator manually shifts the holder or carrier that supports the work-piece or tool, relative to an adjustable table or support and relative to the flat side face of the grinding wheel, according to various curvatures of surfaces or flat surfaces, sometimes with the aid of templates or with the aid of various adjustments of various angularities, according to the specific character of surface shaping that the particular tool or tool bit requires. These two patented disclosures are illustrative of two of the many types of grinding machines to which our system and controls are applicable for effecting stock removal by electrolytic decomposition at the face of the work-piece.

Accordingly, in the drawings, we have shown in Figures 1 and 2, a driving mounting for the rotating conductive element together with an illustrative work-piece and work-holder or support, with a work-table for the latter depicted largely diagrammatically, particularly insofar as its adjustability and movement relative to the rotating grinding wheel are concerned, inasmuch as such adjustability and movement, and the mechanism for effecting them, may take any suitable or known form, and many thereof are well known in the art.

Thus, the apparatus may have a base or main frame **10** which, at its rear, supports a column or vertical standard **11** which, as indicated by the arrows thereon, is rotatively adjustable about a vertical axis and is also adjustable in up-and-down direction; the column **11** supports a wheel head **12**, in which is journaled a grinding wheel spindle **13** which projects both forwardly and rearwardly of the wheel head, and at its rear end carries a pulley **14** which is driven by a belt **15** from a pulley **16** on the shaft of a motor **17**, which is suitably carried by the top of the standard **11**.

The front end of the spindle **13** is appropriately constructed to have or is provided with means for mounting a grinding wheel thereon, as by providing it with a tapered portion **21** (Figures 3–6) that is received into the tapered bore of a flanged sleeve **22**, a nut **23** which is threaded onto the spindle **13** holding the flanged sleeve **22** securely in place. The flanged sleeve 22 is suitably constructed to carry and have secured thereto a grinding wheel which is electrically conductive and which is illustratively and preferably constructed, as is shown in Figures 3 and 4 and as is latter to be described.

When the grinding wheel is so mounted at the front end of the spindle 13 it substantially overlies or overhangs a work-table 24, which is reversibly movable and reciprocable, as indicated by the double-headed arrow in Figure 1, being supported in suitable lengthwise extending ways provided in the cross slide diagrammatically indicated at 25, the later being adjustable or movable, reversibly, as indicated by the double-headed arrow in Figure 2, being suitably carried or supported, for that purpose, on suitable ways provided in the base 10.

The work-piece W, which for purposes of better illustrating certain features of our invention, may be considered to be a block of cemented carbide and suitable means are provided for releasably holding or clamping it to facilitate control of its movement relative to the operative face of the grinding wheel, and such means may comprise a heavy work-holding bar 27, which is provided with a suitable hole or recess 28 in which the work W is received and in which it is clamped securely, as by a clamping screw 29. In the electrolytic "grinding" circuit the work W is to serve as the anode in the electrolytic cell and accordingly suitable provision is made for connecting the work W appropriately into the electrical circuit, and such means may comprise a suitably heavy connector screw 30 by which a conductor may be clamped, carried by and threaded into the work-holding bar 27, as is better indicated in Figures 3 and 5. The work-holding bar 27 may in turn be carried by a vise, generally indicated at 31; the vise may be of any suitable construction and may, for example, comprise a fixed vise jaw 32 and a movable vise jaw 33, between which the bar 27 may be releasably clamped and held, as by the screw 34, manually operable, as by the handle 35. The vise 31 can rest on the work-table 24, with which, when suitably secured thereto, it is movable according as the work-table 24 is moved or actuated as in the above mentioned Patent 2,101,787, or relative to which the vise may be manually moved, as in the above mentioned Patent 2,381,034, in either case to effect the desired or controlled traversing movement or movements of the work W relative to the grinding wheel and to effect the desired feeding and the retracting movement or movements thereof relative to the wheel. As indicated in the drawings, we may provide suitable means such as bolts 36 for clamping the vise 31 at any desired angularity to the work-table 21, where it is desired that the vise move with the table, the bolts being simply omitted when it is desired to manually shift or control the movements of the vise and work-piece W relative to the table. In Figures 1 and 2 the grinding wheel is generically indicated by the reference character CR, and by way of illustration but not by way of limitation it is constructed to present a conductive ring surface at its flat annular side face which, according to the rotational setting about its vertical axis, of the column 11 which supports the wheel head 12, may be given any desired angularity relative to the longitudinal path of movement of the movable work-table 24, according to the needs of any particular grinding job, but for greater simplicity of description the wheel head may be considered as set so that the plane of the operative annular side face of the wheel extends parallel to the line along which the work-table 24 is movable or reciprocable.

A suitable wheel guard 38 is provided, being secured to the wheel head by suitable brackets 39 and being provided with a hinged front cover 40 so that access to the wheel spindle 13 may be gained for mounting or demounting the grinding wheel; the wheel guard with its cover 40 may be shaped substantially as shown in Figures 1, 2, 5 and 6, being cut away as shown to expose a suitable portion of the front face of the wheel where the conductive ring surface is operative and so that the work W may be presented thereto, and to expose a complementary back portion of the wheel for purposes about to be described.

Suitable means are provided to supply a suitable electrolyte to the region of contact or of juxtaposition between the grinding wheel CR and the work W; such means may comprise a broad-mouthed nozzle N, which is preferably adjustably positionable, as by a suitable length of deformable metal tubing 41, which is connected to and supported by a rigid pipe 42 secured to the wheel guard as indicated (see also Figures 5 and 6). Accordingly, deformable tube 41 may be manually bent and set to give the nozzle N the desired location, the mouth of the nozzle being appropriately dimensioned to discharge the liquid electrolyte at and throughout the entire width of the conductive ring surface of the wheel CR, where the work-piece W is presented to the latter.

In Figure 1 we have shown a tank 44 containing liquid electrolyte 45; the latter can be a solution of sodium chloride in water, preferably reasonably concentrated; for example, when the tank is full of pure water, a surplus of common salt may be added thereto so as to leave a quantity of undissolved salt which simply rests on the bottom of the tank. Other salts can be used, but for keeping corrosion at a minimum the very corrosive salts, such as calcium chloride, magnesium chloride and sodium chloride are preferably avoided. Salt, such as sal ammoniac (ammonium chloride) can be used. The carbonates, such as sodium carbonate and potassium carbonate, can be used and in some cases may be preferred, as they are somewhat less corrosive than sodium chloride.

Mounted on the cover plate 46 of the tank 44 is an electric motor 47 which drives a pump 48, the input end of which is connected by a pipe 49 to the inside of the tank 44, with the open end of the pipe being preferably near the bottom of the tank. The output end of the pump 48 is connected by suitable piping 50, and a suitable length of flexible hose 51 to a valve 52 on the end of the pipe 42 which is secured to the hinged wheel guard cover 40. An arrangement such as just described may be used to supply the work-wheel interface adequately with electrolyte; from that location the electrolyte copiously runs out of the bottom of the wheel guard and it and any drippings thereof are eventually collected by a large pan 53 which is built around the top edge of the work-table 24, and as shown in Figure 2, a spout 54 carried by the work-table and movable therewith discharges the pan-collected liquid into a stationary pan 55 that is suitably supported by the base 10 of the machine and which extends throughout the full length of maximum travel of the spout 54 as the latter moves with the work-table. A return pipe 56 extends from the pan 55 to the tank 44.

Many features and advantages of our invention may be realized where the grinding wheel contains or comprises a single rotating conductive face, while many more advantages and greatly increased stock removal capacity may be achieved where, according to other features of our invention, the wheel CR comprises a number of conductive surfaces in coacting relationship with each other and with certain coacting controls; illustrative embodiments of these two forms of electrolytic "grinding" wheels are shown respectively in Figures 3 and 5 and in Figures 4 and 6, and in both forms they are preferably constructed to coact with features of construction already described.

For a readier understanding of various features of our invention, the construction of the single-conductive-faced wheel and its associated electrical energy supply system and controls will first be described, and accordingly, reference may first be made to Figures 3 and 5, in which illustrative and preferred structural features of the wheel are shown, the wheel being generally indicated by the reference character 60. In order also to gain certain advantages in achieving electrical insulation or isolation, the wheel **60** comprises a strong rigid backing B^1 of any suitable cured plastic or the like, such as Bakelite resin; at its center it has molded into it a hole (Figure 3) so that it can be received onto the flanged sleeve **22** and clamped thereon, as by a spanner nut **61** threaded onto the sleeve **22**. As better appears from Figure 3, the backing B^1 has an outer rim-like or annular portion which is of greater thickness than the central portion which is received onto the flanged sleeve **22** and which is clamped between the flange and the spanner nut **61**; this outer portion of greater thickness presents an annular side face, being the left side face as viewed in Figure 3 and being the front face as viewed in Figure 5, and at that face and preferably coaxially therewith the wheel **60** carries a conductive abrasive ring CR^1 which presents, in the illustrative construction, an annular conductive face with which the work-piece W and the electrolyte can coact. This ring CR^1 may be secured to the backing B^1 in any suitable manner, but preferably the ring is constructed so that it is embedded in the non-conductive material of the backing B^1, and preferably it is assembled to the backing itself when the latter is initially molded out of the uncured resinous material which is, during the molding process, made to flow about the faces of the ring excepting its operative face and to become interlocked therewith upon curing of the resinous or other plastic, as under heat and pressure; for better interlocking the ring CR^1 may be a conformation that provides a continuous annular dovetail D (Figure 3), which can be integrally formed at the back of the ring.

As above indicated, it is sometimes desirable that the rotating conductive element in the electrolytic grinding contain abrasive grains and, accordingly, we prefer to describe our invention also in a manner to facilitate embodiment of abrasive grains when and where desired. For the grinding of hard cemented carbides, such as those illustratively mentioned above, suitably bonded diamond grains, as of bort, are usually employed because silicate carbide abrasive grains are hardly as effective on cemented carbides, while alumina grains grind them hardly at all. While, in the illustrative embodiments of our invention we prefer to use diamond abrasive grains, grains of other materials, including silicon carbide and aluminum oxide, may be employed, and as is later made clear, in electrolytic grinding, stock removal may be effected solely by electrolytic decomposition of the metal at the workface without any material abrasive action by any of the grains in the rotating conductive ring or face. Where grains are employed, in order that the ring CR^1 be conductive, the abrasive grains are metal-bonded, and particularly where diamond grains are employed it is preferred that they be embodied in only a relatively small depth in relation to the over-all thickness of the ring itself and accordingly, as is clear from Figure 3, the ring CR^1 comprises an outer abrasive or grain-containing portion **62** of small thickness or depth, and an inner and usually thicker and heavier portion **63** that need not contain any grains and is of metal throughout, serving as a strong rigid support or backing for the thinner diamond-bearing portion **62**. Where a dovetail element D is employed, it forms part of the metal backing portion **63**, as shown in Figure 3, and may be integrally formed or molded therewith or turned or machined to the desired shape.

In making the conductive abrasive ring CR^1, any suitable or known methods or techniques may be employed and need not be described in detail here. For that matter, the patented art describes how, with the use of powdered metal, to make up a unitary integral abrasive ring or annulus having an outer diamond-bearing abrasive portion and an inner support portion wholly of metal. We might note, however, that a usual method of manufacture comprises placing in a suitably shaped mold, to the desired depth, powdered metal that is to correspond to the non-abrasive backing portion and, after leveling or smoothing off, placing thereover a suitable depth of a mixture of

diamond particles and powdered metal, to correspond with the abrasive portion and, after leveling or smoothing off, subjecting the contents of the mold to substantial pressure and then sintering the pressed piece, usually in a protective atmosphere such as hydrogen. By appropriately shaping the mold parts the backing portion **63** may be conformed to have a projecting dovetail part or ring, such as the dovetails D of Figure 3, or, as above noted, and since the backing portion **63** contains no abrasive grains, the dovetails D need not be formed by molding but can be turned or machined to the desired shape after pressing and sintering are completed.

In making the conductive grinding ring, we may use any suitable metal bond appropriate for bonding the abrasive grains and for giving the rings suitable electrical conductivity. In the abrasive-containing portion of each ring, such as the portions **62** of Figure 3, the concentration of abrasive grains should, of course, not be so great as to detrimentally affect electrical conductivity. For finely divided diamond as the abrasive grain, a concentration thereof in the abrasive portion on the order of 25% or less by volume is suitable. Of the many and various metals that are usable for metal-bonding the diamond grains, we prefer to employ a mixture of copper and tin powders in the proportion of about 82% copper and 18% tin, making for both excellent electrical conductivity and good bonding of the grains, and this same mixture of copper and tin is employed in making up the non-abrasive backings, such as the portions **63** of Figure 3, and we set out the just mentioned mixture of copper and tin as an illustration.

The wheel **60** is driven in clockwise direction as viewed in Figures 1 and 3, at a suitable speed to give its conductive ring-face suitable surface speed for appropriate abrasive action, and suitable means are provided to electrically connect its conductive ring CR^1 into the electrical circuit so that the conductive ring is the cathode, for electrolytic decomposition at the face of the work-piece W; such means conveniently comprises a slip ring constructed and coaxially mounted for rotation with the grinding wheel spindle **13**, and a suitable coacting mounting for supporting a brush that bears against the slip ring.

In Figure 3 we have shown such a slip ring at S^1, and it is preferably carried by the non-conductive backing B^1 of the grinding wheel **60**, preferably on the back face of the latter, whereby it is also protected, by centrifugal action, against access thereto of electrolyte which the nozzle N (Figure 5) discharges onto the front face, where the conductive ring CR^1 is operative. Conveniently, the slip ring S^1 is mounted at the back face of the insulating back B^1 in juxtaposition to the conductive ring CR^1 (Figure 3), and it may be secured in position and electrically connected to the conductive ring CR^1 in any suitable manner.

For example, it may be mounted in position after the back B^1 has been molded and cured with the ring CR^1 interlocked, at the front face, with the cured molded insulating material, and then secured in position by a suitable number of equiangularly spaced tension tie-members **65**, which extend through suitable holes in the back B^1 and are anchored, as by threading, at their inner ends to the conductive ring CR^1, in which tapped holes are provided in the backing portion **63** thereof; the outer ends of these tie-members, which preferably take the form of long screws preferably made of copper or of a copper-tin alloy, extend into suitable countersunk holes in the slip ring S^1, thus to clamp the latter securely and concentrically in position at the back face of the wheel back B^1 and at the same time forming multiple electrical connections of high-current-carrying capacity between the slip ring and the conductive ring CR^1.

The screws may be headed, in which case the heads are countersunk into the slip rings, or the screws may be headless, in which case those portions that extend into the countersunk holes in the slip rings may be radially expanded by pressure or by peening to fill up the tapered holes in the slip ring, the taper being appropriately proportioned to the cold-flow characteristics of the metal of the screw shank to facilitate cold-flow expansion thereof as just mentioned. The faces of the slip rings may then be machined, as by turning in a lathe, or by grinding, to be sure that they fall in a plane at right angles to the axis of the grinding wheel and to be sure that the ends of the screws **65** are flush with the faces of their respective slip rings, thus to insure smooth coaction with the brushes of the circuits in which the parts are to coact.

As is better shown in Figure 3, the wheel head **12** has secured to it, as by cap-screws as shown, a bracket **66** which extends in a radial direction relative to the grinding wheel **60** and which is constructed in any suitable way to insulatingly support a brush **67** which is spring-pressed to the left to bear against the face of the rotating slip ring S^1. Suitable means are provided, such as a connector screw **68**, for electrically connecting the spring-pressed brush **67** into the energy-supply and -control circuit arrangements of our system, which is diagrammatically shown in Figure 7.

In Figure 7 the conductive abrasive ring CR^1, with the work W presented to it, are diagrammatically shown, as are also the slip ring S^1 and brush **67** as well as the connector screw **30**, for electrically connecting the work W to one side of the direct-current energy-supply circuit and connector screw **68** for connecting the brush **61** to the other side thereof. In Figure 7 we also indicate an alternating current power circuit, which may be any of the types usually found in factories or industrial plants, and it may be single- or multiple-phase; for illustrative purposes, it may be a three-phase power supply line, usually 60-cycle, and of any suitable voltage; illustratively 440 volts, and in Figure 7 this power line is represented by the reference characters P^1, P^2, P^3. From such a power line or source of alternating current supply, we make provision for converting alternating current energy to direct current energy supply for coaction with the anodic work W and the rotating wheel ring CR^1, with the electrolyte between the latter, for electrolytic decomposition at the face of the work W, all in a manner and under coacting controls to achieve a number of advantages and safeguards, some of which have been indicated earlier above; additional advantages and still further improved actions and results we later describe in connection with the arrangement diagrammatically shown in Figure 8, in which we utilize a grinding wheel having multiple rings like that shown in Figures 4 and 6 mentioned above.

In Figure 7 the broken-line rectangular MA^2, with the parts diagrammatically shown within it, represents a magnetic amplifier of the self-saturating type constructed and arranged for A. C. input and for D. C. output, with appropriate rectifiers and control windings. While the magnetic amplifier MA^2, as well as other such devices later described, are shown as arranged for three-phase alternating current energy input, that is not to be interpreted by way of limitation but rather as illustrative, inasmuch as these self-saturating magnetic amplifiers serve our purposes also when arranged and constructed for A. C. input of other than three-phase, such as single-phase, two-phase, etc., and their functioning, coactions and controls are essentially the same as, and are well illustrated in, the three-phase structures herein disclosed.

In Figure 7 the magnetic amplifier MA^2 comprises a suitable number of reactor units, six in number, for three-phase A. C. input, diagrammatically shown at I, II, III, IV, V and VI, each reactor unit comprising a gapless laminated core of steel of very high permeability, diagrammatically indicated in Figure 7, each core being linked by power or output windings and by appropriate control and/or biasing windings. In the illustration each reactor unit has a power winding PW, and these are interconnected with rectifiers RF in the manner shown, with the three-phase power line P^1, P^2, P^3, connected by conductors **71**, **72**, **73** respectively to the input terminals of the magnetic amplifier MA^2, those input terminals respectively, as shown, between adjacent paired rectifiers RF—RF; direct current energy output is delivered through the conductors **74**, **75**, leading from the interconnected power windings PW, as shown in Figure 7.

In the illustrative embodiment each of the six reactor units I, II, III, IV, V, VI is provided with two control windings W^1, W^2; control windings W^1 are connected in series, as shown, and control windings W^2 are also connected in series as shown; in each reactor unit, therefore, each control winding will have similar effect, when their respective series circuits are properly energized.

The above described parts of the magnetic amplifier MA^2 are, in each of the reactor units, so proportioned to each other that when interconnected as shown and as above described they will be capable of delivering a direct current output which, illustratively, can be on the order of 30 volts at an amperage on the order of 140 amperes, when energized on the input side by three-phase alternating current of 60 cycles at suitable voltage; since the construction, action and operation of such a self-saturating magnetic amplifier are known, they need not be in detail herein described. It might, however, be noted that the just described magnetic amplifier MA^2 is commercially available. Its A. C. input voltage may be on the order of 32 volts, in which case a step-down transformer T is interposed as is diagrammatically indicated in the drawings.

The D. C. output circuit **74**—**75** we connect to supply unidirectional current to the electrolytic cell that comprises the conductive abrasive ring CR^1 and the work W, with the connection so made that the work W is anodic, and by suitable conductors and circuit connections as shown in Figure 7 connections are accordingly made to the connector screw **30** and to the slip ring brush connector screw **68**, but in making those connections we insert into the electrolytic cell circuit a resistance element R^4, preferably of relatively low resistance, on the order of and illustratively 0.001 ohm; with unidirectional current flowing to the work-wheel interface, a voltage drop is produced across the terminals of resistance R^4 that it directly proportional to the current flowing across the work-wheel interface. Thus, with a current flow of 100 amperes the voltage drop across resistance R^4 is 0.1 volt; with a current flow of 10 amperes the voltage drop is 0.01 volt. The voltage drop across resistance R^4 we utilize as a signal for coactions and controls later described.

Also, in making the connections to supply the D. C. energy output of the magnetic amplifier MA^2 to the work-wheel interface we provide a resistance R^5, of about 3 ohms, which is shunted across the D. C. output circuit **74**—**75**, being thus arranged in parallel with the work-wheel circuit; resistance R^5 provides a small load on the D. C. output side of the magnetic amplifier so that the operation of the latter and of associated circuits need not be undesirably affected by an open-circuit value of voltage were the direct current circuit actually interrupted at the work-wheel interface, as by removal of the work W from coacting relation with the electrolyte and the conductive ring CR^2, and accordingly there is always effective, across the work-wheel interface, a definite D. C. voltage even with no current flow through the electrolytic interface cell. This D. C. voltage at the interface we desirably maintain substantially constant at any suitable value up to maximum, throughout certain ranges of conditions that can exist in the electrolytic cell at the work-wheel interface. An illustrative interface voltage for this purpose may be, say, 10 volts.

Various factors at the interface can cause departures from the desired value of constancy of D. C. output voltage across the circuit work-wheel interface, and such departures, conveniently measured by the voltage across the small load resistance R^5 in which they are reflected, we cause to become operative to affect the interconnected control windings W^2 of the magnetic amplifier MA^2, thus to modify the action of the latter in appropriate directions to restore the voltage of the D. C. output to substantially the selected value. For that purpose we prefer to employ a self-saturating magnetic amplifier MA^1, which we arrange to respond to these voltage departures, preferably in conjunction with suitable means arranged to provide a reference voltage, preferably adjustable so that the standard of voltage constancy may be changed.

For example, from one of the phase of the three-phase power circuit P^1, P^2, P^3 we connect, as by conductors **77**, **78**, a voltage regulator or stabilizer T^1, which may be of any suitable or known construction, to provide at its output 60-cycle alternating current energy at a fixed or constant voltage, such as 115 volts, in order that thereby variations or fluctuations in the voltage of the three-phase supply line be not reflected in the control circuits of the system; accordingly, conductors **79**, **80** lead from the output side of the voltage stabilizer and provide a constant voltage circuit to which other regulating or control apparatus may be connected.

Among the latter is a circuit and apparatus for supplying the serially connected control windings W^1 of the magnetic amplifier MA^2 with unidirectional current to provide a steady operating bias for the magnetic amplifier, and these comprise a transformer T^3 that has its primary connected across the steady voltage circuit **79—80**, and with its secondary connected with suitable full-wave rectifying means, such as a full-wave mercury vapor rectifier V^1 provided with two anodes connected respectively to the secondary terminals of the transformer T^3; full-wave rectified current is thus available at the mid-point or central tap of the transformer secondary, and the common cathode of the rectifier tube, these being connected, by conductors **69**, **70**, to the serially connected bias or control windings W^1 of the magnetic amplifier MA^2, suitable condensers, such as C^1, C^2, and resistances R^9, R^{10}, being included in the circuit as shown for smoothing out the unidirectional output of the full-wave rectifier unit. One of these resistances, such as resistance R^9, may be adjustable, as by a tap as shown, for setting the value of unidirectional biasing current supply to the serially connected windings W^1. While the resulting biasing current is relatively small, the many turns of the windings W^1 of the control fields of the amplifier MA^2 provide the desired bias for the proper functioning of the magnetic amplifier.

Also connected across the constant voltage circuit **79—80** is a transformer T^2, connected thereto through an adjustable resistor R^{30} and having its secondary winding connected to two terminals of a full-wave rectifier bridge RB, which has its output terminals connected across a resistance R^8; these parts may be constructed and proportioned so that the D. C. voltage at the output terminals of the rectifier bridge RB is on the order of 32 volts or so, that voltage appearing across the resistance R^8, and from the latter, by appropriate adjustable taps and associated resistances, a selectable reference voltage, such as 10.0 volts, may be derived, where it is desired to maintain the D. C. input to the work-wheel interface constant at 10.0 volts.

The selected reference voltage and the work-wheel circuit voltage across resistance R^5 are brought into opposition to one another in a circuit which includes the serially connected control windings W^3 of the magnetic amplifier MA^1. The latter is in general of similar construction and arrangement as the magnetic amplifier MA^2 above described, excepting that, for its purposes, it can be of much smaller D. C. output capacity, a capacity appropriate to energize the control windings W^2 of magnetic amplifier MA^2. Like the latter, it may comprise six reactor units diagrammatically indicated by the reference characters VII, VIII, IX, X, XI, XII, each unit comprising a gapless laminated core composed of steel of suitably high permeability, with their respective output or power windings PW^1 interconnected, with rectifiers RF^1 as shown, the three-phase power line P^1, P^2, P^3 being connected by conductors **81**, **82**, **83** between the respective paired rectifiers as shown, the unidirectional or direct current energy output being furnished by connections, as shown, to the amplifier output terminals **84**, **85**. As above noted, the control windings W^3, one for each reactor unit, are connected in series, and so also are the control windings W^4, one for each of the reactor units of the amplifier MA^1, the control windings W^4 being energized, as is later described.

As above noted, control windings W^3 of magnetic amplifier MA^1 are connected to respond to the difference between the D. C. work-wheel supply circuit, that is, the voltage across resistance R^5, and the selected value of reference voltage derived from the output terminals of the full-wave rectifier bridge RB, more specifically, as the latter reference voltage may be derived by an adjustable tap **86** coacting with the resistance R^8 in conjunction with a series resistance R^7 and an adjustable series resistance R^6, which may be arranged as shown, together with a suitable condenser or capacitance C^5 connected as shown and which may serve to smooth out the full-wave rectified output of the rectifier bridge RB.

Having set the tap **86** at that point where the voltage drop across the left-hand portion of resistance R^8 is equal to the value at which the voltage of the D. C. work-wheel circuit is to be kept constant, illustratively 10 volts, no current flows through the control windings W^3 of the magnetic amplifier MA^1 so long as the work-wheel supply voltage across resistance R^5 is 10 volts, for the parts are so connected that the voltage across resistance R^5 is opposed to the selected reference voltage, but when conditions arise at the electrolytic cell at the work-wheel interface to cause the D. C. output voltage of magnetic amplifier MA^2 to fall below the selected voltage of say 10 volts, the resulting current in the series circuit, which includes resistances R^6, R^7 and the control windings W^3, causes an increase in the D. C. output, at output terminals **84**, **85** of the magnetic amplifier MA^1, and that increased D. C. output, being supplied by conductors **88**, **89**, through a series resistor R^3 to the serially connected control windings W^2 of magnetic amplifier MA^2, affects the action of the latter to increase its output at the output circuit **74—75** and thus restore the voltage across the latter and across resistance R^5 to the selected reference voltage, illustratively 10 volts.

The complete circuit in which the selected reference voltage and the D. C. work-wheel supply voltage are thus made effective in opposition to each other will be seen to extend from the left-hand end of resistance R^8, through adjustable resistance R^6 through the serially connected control windings W^3 of magnetic amplifier MA^1, then by conductor **91** to one terminal of the D. C. work-wheel input circuit, through resistance R^5, then from the other terminal of the D. C. work-wheel input circuit and conductor **92**, through resistance R^7 and through the tap **86** to the other side of the effective or selected portion of the resistance R^8.

However, and as above indicated, we make provision for controlling also the current output of the magnetic amplifier MA^2, in order to guard against certain conditions that can arise at the work-wheel interface, illustrative examples of which are later set forth. As above described, the smaller-capacity magnetic amplifier MA^2 also has control windings W^4 which are serially connected, and these we cause to respond, in preferred coaction with, or in relation to, the action of the control windings W^3, in response to changes in current or amperage flowing to the electrolytic cell at the work-wheel interface, and for this purpose we conveniently employ the above described series resistance R^4 which, by the voltage drop effective thereacross, is a measure, as above noted, of the amount of unidirectional current flowing to the work-wheel interface. This voltage drop across the series resistance R^4 is of course unidirectional, and we make provision for causing the control windings W^4 of the magnetic amplifier

MA^1 to become controllably responsive to changes in its value.

For this latter purpose we prefer first to convert the D. C. signal voltage across resistance R^4 to an alternating voltage and accordingly we provide a converter vibrator V^7, which is constructed to effect current reversals at the rate of 60 cycles per second, where the main power supply, such as the three-phase power line P^1, P^2, P^3, is of 60 cycles. The converter vibrator may be of any suitable or known construction and comprises a synchronously vibrating magnetically responsive reed or armature **95**, which is set into synchronous vibration by a suitable winding and core construction **96**, of which the winding is connected, as by conductors **97**, **98**, to the stabilized-voltage circuits **79—80**, preferably through a suitable energizing control device, such as an adjustable resistance R^{17}.

The vibrator V^7 coacts with the primary winding of a transformer T^5 having its mid-point connected by conductor **101** to one side of the series resistance R^4 and having its terminals connected respectively to two spaced contacts as shown and which are alternately contacted by the vibrating element **95** which, by conductor **102**, is connected to the other side or terminal of the resistor R^4. Accordingly, unidirectional current, proportional to the voltage drop across resistance R^4 and hence proportional to the current flowing across the work-wheel interface, is alternately directed in opposite directions through the two halves of the primary winding of transformer T^5, producing in the secondary winding of the latter a 60-cycle alternating potential that is always proportional to the voltage drop across the series resistance R^4 and to the unidirectional current flowing to the work-wheel interface electrolytic cell.

This 60-cycle alternating potential, thus produced in the secondary transformer T^5, we now amplify and ultimately, after sufficient amplification, rectify for supply to the control winding W^4 of the magnetic amplifier MA^1, so as to affect the output at output terminals **84—85**, of that magnetic amplifier, that modified output energy in turn being supplied to the control windings W^2 of the magnetic amplifier MA^2. The magnetic amplifier MA^1, which, as above noted, may be of an output capacity much smaller than that of the power supply magnetic amplifier MA^2, since the former need supply only sufficient energy to affect the control windings of the latter, may have a rating of a D. C. output on the order of 0.030 ampere at 400 volts with a three-phase 60-cycle input at 440 volts so that, as above described, its input side may be connected to the three-phase power supply line P^1, P^2, P^3.

As illustrative of a suitable amplified rectifying circuit arrangement for the alternating potential produced in the secondary of transformer T^5, we may employ a suitable succession of suitably coupled vacuum tubes of the triode type, arranged for convenient and appropriate biasing of their grids and preferably also arranged for appropriate phase control. Thus we may provide first a four-stage amplifier, generally indicated by the reference character AM^4, comprising two twin-triodes V^3, V^4 coupled by suitable resistances and condensers substantially as shown so that alternating signal voltage, proportional to the current flowing to the work-wheel electrolytic cell, as produced in the secondary of transformer T^5 is materially amplified, suitable plate voltage being obtained by way of a transformer T^4 having its primary connected across stabilized voltage circuit **79—80** and having its secondary winding terminals and mid-point connected, as shown, in relation to a full-wave vacuum rectifier tube V^2, with stabilizing or smoothing condensers C^3, C^4 and resistance R^{18}, all connected as shown to the circuit conductors **103**, **104**, which respectively represent the B+ and the B— sides of the amplifying circuits as shown; in this manner a potential of several hundred volts, such as 500 volts or 600 volts, is made available for the amplifier circuits.

The resultant amplified voltage signal, effective in the output circuit of the twin-triode amplifier tube V^4, is applied to the grids of a twin-triode amplifier tube V^5, through the transformer T^6, which is interconnected therewith and with the plate voltage circuit **103—104** as shown, including suitable means, also as shown and including adjustable resistance R^{27}, for biasing the grids of the tube V^5; by adjusting the parts, including the adjustable resistance R^{27}, the grids of the tube V^5 are biased well below cut-off so that the tube V^5 permits current to flow in its output circuit, which includes the primary of the transformer T^7, only when the above-mentioned signal voltage, derived initially by the voltage drop across the resistance R^4 that carries the current to the work-wheel electrolytic cell, reaches a value corresponding to that value of current flow to the work-wheel interface which it is desired, as is later more fully explained, not to be exceeded; by adjusting the bias of the grids of the tube V^5, illustratively by setting the resistance R^{27}, this limiting value of current flow to the work-wheel interface may be changed and thus the standard of operation at which current flow to the work-wheel face is limited may be changed according to the particular conditions or circumstances met with in the electrolytic cell at the work-wheel interface.

The A. C. signal passed by the tube V^5 as the current to the work-wheel interface begins to exceed the selected limiting value is passed on, through the transformer T^7 and connections as shown, to the twin grids of a twin-triode amplifier tube V^6, and is synchronous with the alternating plate voltage supplied to the plates of tube V^6, inasmuch as the latter, aside from effecting further amplification, is to achieve also full-wave rectification so as to furnish direct current, in response to the initiation of the above-mentioned A. C. signal, to the control windings W^4 of the magnetic pre-amplifier MA^1. As above described, the series resistance R^4 in circuit with the work-wheel interface converts the current flow through the latter into a D. C. potential drop or D. C. signal voltage which varies directly as interface conditions vary the D. C. current flow across the work-wheel interface, and the above-described vibrator-converter, utilizing the synchronously operating vibrating element **95** and the coacting transformer T^5, converts that initial D. C. signal voltage into an A. C. signal appearing as a 60-cycle alternating potential at the output terminals of the secondary winding of transformer T^5. The A. C. signal varies directly as and is proportional to the D. C. signal. As is also clear from the above, the plate voltage supplied to the plates of tube V^6 is also alternating and of 60 cycles. The two are phased in synchronism in any suitable way, as by adjusting one or more suitable impedances in the circuit of either or both of these A. C. potentials, illustratively as by adjusting a variable condenser C^X in the output or coupling circuit between the tubes V^3 and V^4. Consequently, when the amplified A. C. signal, thus phased in synchronism with the alternating plate voltage supplied to the plates of tube V^6, is passed to the latter, conduction occurs in the respective sections of tube V^6 during the successive half-cycles of each complete cycle, and full-wave rectified current appears in the cathode return circuit in which are included the control windings W^4 of pre-amplifier MA^1. The circuit thus also achieves further amplification as well as full-wave rectification in its tube V^6 for supply of direct current, through conductors **105**, **106** to the control windings W^4 of the magnetic amplifier MA^1.

More specifically, we provide a transformer T^9, of which the primary winding is connected to the stabilized-voltage circuit **79—80** as shown, and of which the secondary has its terminals connected to the two plates of the tube V^6 with the mid-point of the secondary connected, through a resistance R^{16}, to the conductor **105** that leads to one side of the control windings W^4; the other conductor, **106**, that leads to the control windings W^4 is connected to the twin cathodes. Accordingly, the secondary winding of transformer T^9 can supply the control windings W^4 of magnetic amplifier MA^1, after rectification of alternate half cycles by the two sets of electrodes in the twin-triode tube V^6, with unidirectional current, smoothed out by the condenser C^{11}, of a magnitude determined by the grids of the tube V^6. This unidirectional current may be a current for biasing the magnetic amplifier MA^1, where D. C. bias is needed or utilized in the operation thereof, and such a steady biasing current may be achieved by biasing the two grids of the tube V^6, as by the adjustable resistance R^{28} which is connected to the mid-point of the secondary winding of transformer T^7 and which is interconnected with the B+ and B− conductors **104**, **103** as shown. When the voltage signal across the resistance R^4, which carries the current to the work-wheel interface, begins to exceed the value corresponding to the desired current-limiting value, it is passed by the tube V^5 in the manner above described because its grids are then driven above cut-off and permit current to flow in the plate circuits and through the primary of transformer T^7, whereupon the secondary of that transformer affects in like degree the grids of the full-wave rectifying tube V^6 so that a corresponding flow of unidirectional current takes place through conductors **105**, **106** to the control windings W^4 of the magnetic amplifier MA^1, over and above the above-mentioned steady D. C. biasing current as set by the grid-bias resistance R^{28} as above described. The resultant action on the magnetic amplifier MA^1 is to reduce its output and hence to reduce the energy supply to the control windings W^2 of power magnetic amplifier MA^2, and thus restore the current supplied to the work-wheel interface to the selected limiting value.

For any particular type or kind of electrolytic grinding operation the maximum safe current flow to the electrolytic cell at the work-wheel interface may be easily determined; for example, it may be empirically determined by actual tests, as by observing, for different relations of the work W to the conductive abrasive ring CR^1, the current flow to the work-wheel interface and the voltage thereacross, when detrimental arcing takes place across the work-wheel interface and through the interposed electrolyte, and for such purposes, as well as for purposes of setting the various manual controls above described, we may provide a voltmeter M^5 and an ammeter M^6 (with shunt resistance) connected into the circuit of the work-wheel electrolytic cell. Thus it may be found that, for a given type of grinding operation, the critical current value at which detrimental arcing is produced is, say, 50 amperes, and in such case current-limiting action of the system may be set to take place as soon as current flow to the work-wheel interface reaches, or starts to exceed, 40 amperes; accordingly, the resistance R^{27} is set to bias the grids of the tube V5 to permit current flow to the transformer T^7 in response to increase in the current-responsive voltage signal produced across the resistance R^4 in the work-wheel circuit above that value of voltage drop corresponding to a flow of 40 amperes to the electrolytic cell; with the resistance R^4 having a value of 0.001 ohm so that the critical signal voltage across resistance R^4 is 0.04 volt, no current-limiting action takes place so long as the current flow to the work-wheel interface is 40 amperes or less; during these conditions or circumstances, however, the voltage applied to the work-wheel electrolytic cell circuit at the amplifier output circuit **74**—**75** is maintained substantially constant at a voltage of, say, 10.0 volts by the control action of control windings W^3 of the amplifier MA^1, in its control section upon the control windings W^2 of the power magnetic amplifier MA^2, due to the pre-setting of the reference voltage resistor R^8 to 10.0 volts, as against which reference voltage, changes in the signal voltage across resistance R^5 (shunted across the work-wheel circuit) function, in the circuit **91**—**92**, in which the control windings W^3 of the control amplifier MA^1 are included, to maintain the D. C. voltage of the output circuit **74**—**75** of the power magnetic amplifier MA^2 substantially constant.

The current flowing through the electrolyte at the work-wheel interface, for electrolytic decomposition of the workpiece, may thus vary, below the preselected critical value of 40 amperes, according as changes in relationship between work-piece W and conductive ring CR_1 take place that do not call for, or permit, current flow greater than the pre-set limiting value of 40 amperes. However, should any such change in conditions at the work-wheel interface take place as would call for or permit current flow through the electrolyte of an amount greater than the selected limiting value of 40 amperes, the signal voltage across the series resistance R^4 begins to exceed the above-mentioned selected critical value of 0.040 volt and that, as above described, immediately causes corresponding amplified energization of the control windings W^2 of the power amplifier MA^2, in response to the amplified or multiplied effect caused by control windings W^4 in the pre-amplifier MA^1, the latter having, in its control windings W^4, a more rapid response than is caused therein by the voltage-responsive control windings W^3; as a result the effects of the latter control windings (W^3) are in effect overpowered by the action of the current-responsive control windings W^4, with the result that the current output of the power magnetic amplifier MA^2, in its output circuit **74**—**75**, is reduced to, or prevented from exceeding, the selected limiting value of current, namely, 40 amperes in the above illustration, and this action takes place even though the D. C. output voltage, in the output circuit **74**—**75**, falls below the selected reference voltage (illustratively 10.0 volts) that is selected at the potentiometer variable resistance R^8. Accordingly, whatever condition, at the work-wheel interface, that would otherwise bring about excessive or damaging current flow across the work-wheel interface, is prevented from causing any damage and the current continues to be limited, at substantially 40 amperes, so long as that particular condition exists in the electrolytic cell. In that manner electrolytic grinding may proceed safely, in spite of the many variables, some of which are noted above, that can be introduced by not only various types of grinding operations but also by varying conditions accompanying any particular type of grinding operation. Thus, there may be relative traverse between grinding wheel and the work-carrying table **24** (Figures 1, 2 and 3), as by longitudinal movement or reciprocation of the table **24**, and in the course of such traverse apparent or actual area of contact between the work W and the conductive ring CR^1 may vary as above pointed out; there may be relative infeed movement between the work W and the conductive abrasive ring CR^1, as by inward movement or feed of the cross slide **25**, and in that manner also variables, such as changes in area of actual or apparent contact, or the like, may take place; or where the work W is manually manipulated, as in "off-hand" grinding or as in the above-mentioned Patent 2,381,034, generally similar and also other variables occur or are introduced at the work-wheel interface. These are cited as illustrative of varying circumstances with which our invention successfully copes, by coactions and interacting controls, with illustrative settings, all as above described.

According to certain other features of our invention, and in order to achieve still further practical advantages, we provide the grinding wheel CR of Figures 1 and 2 with more than one conductive abrasive ring and bring each of the latter into a coacting relation with an energy-supply and control or regulating system of the kind above described in connection with Figure 7, all as is diagrammatically shown in Figure 8, with an illustrative multiple-ring grinding wheel, such as is better shown in Figures 4 and 6. Referring to Figures 4 and 6, the grinding wheel **110** there shown may be constructed like the above described single-ring wheel **60** of Figures 3 and 5 except that it is provided with three coaxial conductive abrasive rings CR^2, CR^3, CR^4, embedded in a cured molded non-conductive backing B^2 so as to present their aligned faces at the front annular face of the backing B^2, the latter carrying three coaxially arranged sliprings S^2, S^3, S^4 at the back face thereof and internally connected respectively, by tension tie-members **65**, to the conductive abrasive rings C^2, C^3, C^4. The latter may, in their specific construction, be made as above described in connection with the conductive abrasive ring CR^1 of the wheel **60** of Figures 3 and 5, having an abrasive-grain-containing portion **62** backed up by a heavier inner portion **63**, which may be given a dovetail shape for interlocking with the molded material of the backing B, as earlier above described, with the conductive tie-members **65** anchored at their respective ends in the portion **63** and in the slipring, all as above described.

This illustrative multiple-ring wheel **110**, when mounted on the driven spindle **13** as shown in Figures 4 and 6, thus presents coaxial aligned conductive surfaces for coaction with the workpiece W, the nozzle N, which discharges the electrolyte as shown in Figure 8, being of a width of mouth to spread the discharged electrolyte onto and throughout the over-all width of the multiple-conductive grinding surfaces of the rings CR^2, CR^3, CR^4 at the region thereof where the work W is presented to them for stock removal by electrolytic decomposition, the workpiece W being anodic and being connected into the electrical circuit of Figure 8 by a circuit conductor secured by the connector screw **30** (Figure 4).

Electrical connection with the conductive abrasive rings CR^2, CR^3, CR^4 is effected, as the wheel **110** rotates, by their respective sliprings S^2, S^3, S^4, with which coact respectively stationary spring-pressed brushes **67**^{a}, **67**^{b}, **67**^{c} (Figure 4) that are carried by the brush bracket **66**, the latter carrying insulated connector screws **68**^{a}, **68**^{b}, **68**^{c}, by which individual circuit conductors may be connected in circuit with the respective brushes and hence with the respective conductive abrasive rings.

It will be understood that in illustrating the grinding wheel **110** of Figures 4 and 6 with three conductive abrasive rings CR^2, CR^3, CR^4, that is not to be interpreted by way of limitation but rather by way of illustration since, as will better appear later, in connection with the energy-supply and -control system and arrangement shown in Figure 8, the number of conductive rings employed may be varied; they may be less than three in number or more than three. In Figure 8, as in the arrangement above described with respect to Figure 7, we again provide a saturatable magnetic amplifier, which may be similar to the magnetic amplifier MA^2 and which we have therefore represented, in Figure 8, as a whole, by the rectangle marked MA^2, connected to the three-phase power line P^1, P^2, P^3 by conductors **71**, **72**, **73**, for converting alternating current energy to direct current energy, the output of which appears in the D. C. output circuit **74**, **75**, to one side of which the work-piece W is connected at the connector screw **30** so that the work is anodic, and to the other side of which the conductive abrasive rings CR^2, CR^3, CR^4 are connected at the brush-holder connector screws **68**^{a}, **68**^{b}, **68**^{c} respectively, so that the several electrolytic cells formed at the respective work-ring interfaces are connected in parallel, but in the respective circuits leading to the sliprings and conductive abrasive rings we insert resistances R^{42}, R^{43}, R^{44} each of which can have the same characteristic or value as the resistance R^4 of Figure 7. As is now clear from the description of Figure 7, each of these three resistances may serve, by the voltage drop that occurs across its terminal ends, as a measure of the current flowing to the conductive ring and electrolytic work-ring electrolytic cell in its circuit. Bridged across these parallel electrolytic cell circuits, as by connecting it across the D. C. output circuit **74**, **75** of the amplifier MA^2 (as in Figure 7), is a resistance R^5, which can be the same in illustrative value as resistance R^5 of Figure 7. And the potential across it corresponds to the D. C. voltage supplied to the multi-ring electrolytic grinding wheel **110** and the work-piece W, with the electrolyte therebetween.

In Figure 8 we also employ a lower-capacity saturatable magnetic amplifier, which can be the same as the device MA^1 of Figure 7 and hence we have represented it diagrammatically in Figure 8 by the rectangle designated MA^1, with its input windings connected through conductors **81**, **82**, **83** to the three-phase power line P^1, P^2, P^3, and with its direct current output terminals **84**, **85** connected by conductors **88**, **89** respectively to the control windings W^2 of power amplifier MA^2; it has the same control windings W^3, W^4 as in Figure 7, and of these control windings W^3 are connected, by conductors **91**, **92** in series with the signal voltage resistance R^5 and with the adjustable reference voltage resistance R^8, so the control windings W^3 respond to modify the output of the pre-amplifier MA^1 in response to the difference between the signal voltage across resistance R^5 and the reference voltage across the adjustable resistance R^8, as was described above in connection with Figure 7.

Control windings W^4 of the pre-amplifier MA^1 we arrange to coact with and to respond to changes in current flow to the respective electrolytic cells at the work-ring interfaces, as evidenced by the signal voltages that occur as potenial drops across the resistances R^{42}, R^{43}, R^{44} preferably in the manner and by means of illustrative circuit arrangements as are shown in Figure 8, making provision for converting this unidirectional signal voltage to an alternating potential, which is amplified and synchronized and then rectified for supplying to the preamplifier control windings W^4, according to the principles above described in connection with Figure 7.

Accordingly, we provide three converter vibrators, V^{71}, V^{72}, V^{73}, with their energizing windings **96** connected, as shown, to the steady voltage circuit **79**—**80**, and with their respective vibrating elements **95**^{a}, **95**^{b}, **95**^{c} connected respectively by conductors **102**^{a}, **102**^{b}, **102**^{c} to the respective wheel-ring sides of the resistances R^{42}, R^{43}, R^{44}, while conductor **101**, connected to the common sides of these three low resistances, connects them to the mid-points of the transformers T^{51}, T^{52}, T^{53} respectively associated with the synchronized vibrating converters V^{71}, V^{72}, V^{73}.

The secondary windings of these three transformers T^{51}, T^{52}, T^{53} thus produce alternating potentials, of 60 cycles, which correspond and are proportional respectively to the unidirectional current-responsive signal voltages produced; each of these alternating potentials is then amplified, as was described above in conection with Figure 7, each by a multi-stage amplifier like the amplifier AM^4 of Figure 7, and in Figure 8 the corresponding amplifiers are diagrammatically indicated by the reference characters AM^1, AM^2, AM^3.

These amplifiers AM^1, AM^2, AM^3 each include an output transformer like the transformer T^6 of Figure 7, which are respectively connected, as indicated, to the push-pull or twin-triode amplifier tubes V^{51}, V^{52}, V^{53}, with grid-bias control through adjustable resistance R^{27}, as in Figure 7, and for this purpose the midpoints of the amplifier output transformers T^6 may be connected in common to the tap on the grid-control resistance R^{27}. The respective output transformers T^{71}, T^{72}, T^{73} have their secondaries connected in parallel as shown, with their midpoints connected in common to the grid-bias control resistance R^{28}, so that the output of one or more or all, in response to the corresponding synchronized and amplified A. C. signals derived respectively as respective functions of the three currents flowing to the respective work-wheel interfaces, may be passed on for full-wave rectification and amplification by the twin-triode amplifier tube V^6 and as thus rectified supplied, from the tube cathode circuit, to the control winding W^4 of the magnetic pre-amplifier MA^1, by way of conductors **105**, **106**.

In effect, in the arrangement of Figure 8, for each of the three work-wheel interfaces and their respective unidirectional current-responsive signal voltages, we provide the same electronic devices and circuit for converting the latter to an alternating potential and for amplifying and phasing the latter and for full-wave rectification just the same as that shown in detail and in Figure 7 and fully described above, except that, as above noted, any of the three amplified alternating signal potentials or currents, synchronized with each other and phased in relation to the full-wave rectifier tube V^6, can individually, or conjointly with one or all of the rest, affect, through the rectifier tube V^6, the windings W^4 of the magnetic amplifier MA^1; for these reasons most of the parts of these three circuits are shown only diagrammatically or schematically in Figure 8, and the details need not be further shown nor described.

As above noted, with more than one conductive abrasive ring as in Figures 4, 5 and 8, we are enabled very materially to increase the capacity for stock removal by electrolytic decomposition at the work face in that higher total current and also higher current densities may be used at the work-wheel interfaces with safety and at high efficiency; for example, still assuming that the critical arcing current for each work-wheel interface is 50 amperes, we may again select 40 amperes as a safe upper limit of current flow in each work-wheel circuit, making a total current flow of 120 amperes. With more conductive rings and associated slip rings, the total current can be correspondingly increased. For such higher outputs of the magnetic power amplifier MA^2 appropriate changes in settings or controls are correspondingly made, and the same is true as to the magnetic pre-amplifier MA^1 for appropriate coaction of its output with the control windings W^2 of the power amplifier MA^2.

In operation of the system, so long as conditions at each of the three work-wheel interfaces are such that the selected limiting or maximum safe value of current, illustratively 40 amperes, is not exceeded in any one or more of the work-wheel interfaces, the corresponding D. C. signal voltages, being the voltage drops across the respective resistances R^{42}, R^{43}, R^{44}, do not reach a value to drive the grids of the corresponding tube V^{51}, V^{52}, or V^{53} above cut-off, and no current flows in the circuit of conductors **105**, **106** to the control windings W^4 of the pre-amplifier MA^1. The latter, therefore, continues to regulate the output of the power amplifier MA^2 for substantially constant voltage across its output circuit **74—75**, in response to the coaction of the voltage across resistance R^5 with the selected reference voltage provided in the output circuit of the rectifier bridge RB for corresponding control of the energization of the control windings W^3 of the pre-amplifier MA^1. With a greater current output for electrolytic work-face decomposition, the D. C. voltage thus maintained substantially constant across the work-wheel interfaces may be higher than the illustrative 10-volt value set forth in the illustrative example described in connection with Figure 7; it may be on the order of 15.0 volts or more. The respective currents across the work-wheel interfaces may thus vary below the pre-selected safe value of 40 amperes and these currents may vary relative to one another, according as changes at the respective work-wheel interfaces take place that do not call for or permit current flow greater than the selected limiting value of 40 amperes; for example, the work W may be traversed or reciprocated relative to the several conductive wheel elements so that it is operatively related to one or more but not to all of them, so that current flow from one or more conductive wheel elements to the work-face does not take place. Or, the work W may be juxtaposed only partially to one conductive element and wholly juxtaposed to another, thus effecting differences in areas of actual or apparent contacts. Or, as a further illustration, where there is actual contact, pressure of contact with one conductive wheel element might be greater than that at another. And so on.

However, should any condition arise at any of the work-wheel interfaces to permit or call for current flow greater than the selected limiting value, such as 40 amperes, the D. C. signal voltage drop across the series resistance R^{42}, R^{43}, or R^{44} of the corresponding work-wheel interface is correspondingly increased in the corresponding converter and amplifying circuit, driving the grids of the corresponding tube V^{51}, V^{52}, or V^{53} above cut-off and permit the greatly amplified converted alternating potential or current to be passed on to the rectifying and amplifying tube V^6 by the corresponding intervening transformer T^{71}, T^{72}, or T^{73}, the materially amplified output of the tube V^6 energizing the control windings W^4 of the pre-amplifier MA^1 so that its correspondingly changed output supplied to the control windings W^2 of the power amplifier MA^2 causes the latter to reduce its output, by reduction in its output voltage, to a value such that the maximum or safe limiting current value of 40 amperes cannot be exceeded in the affected work-wheel interface; the latter is thus protected against damaging action or arc-over. The operation of the system can thus continue safely, under the preponderant regulating or control action of the control windings W^4 of the pre-amplifier MA^1 over the voltage regulating control windings W^3 thereof, for so long as the condition exists at any one or more of the work-wheel interfaces to bias or drive the grids of the corresponding tube V^{51}, V^{52}, or V^{53} above cut-off. Once the adverse condition at the one or more of the work-wheel interfaces is removed or rectified or changed in favorable direction to call for current flow in the corresponding work-wheel interface or interfaces of less than the maximum safe value so that the grids of the corresponding tubes V^{51}, V^{52}, or V^{53} are restored to normal bias below cut-off, the energization of control winding W^4 of pre-amplifier MA^1 ceases and the control action of the pre-amplifier is taken over by or restored to control windings W^3 for substantially constant voltage control across the parallel work-wheel interfaces.

It will now be clear and better understood that in the several amplifying circuits, one for each of the work-wheel interfaces, we make provision for very substantial energy amplification, the latter being facilitated by conversion, in each amplifying circuit, of the corresponding D. C. signal voltage to an alternating potential; in this manner we are enabled to achieve additional advantages in the direction of protecting the multi-ring wheel **110**, particularly in materially reducing or guarding against detrimental electrolytic action between rings or conductive elements of the electrolytic grinding wheel. Such electrolytic interaction between conductive rings or elements can take place if material differences arise between the potential drops across the several work-wheel interfaces, all of which have the work W as a common electrode during electrolytic action on the work-face; if such a material difference were to arise between the potentials of any two of the conductive elements CR^2, CR^3, CR^4 (Figure 8), a current can flow from one to the other through the electrolyte. The more positive conductive element feeds current through the electrolyte on the wheel surfaces to its more negative neighboring conductive ring, causing electrolytic etching at the more positive abrasive ring.

Accordingly, we preferably make the series resistances R^{42}, R^{43}, R^{44} very small in ohmic value; illustratively each may have a resistance on the order of 0.0001 ohm. As a result, the voltage drop across each, even at maximum curents flow therethrough, is very small, on the order of only several millivolts. Assuming a maximum current flow in each work-ring circuit of 100 amperes, the voltage drop across each resistance is only 0.01 volt. At maximum current flow of 40 amperes in each, as in the illustration above set forth, the voltage drop across each resistance is 0.004 volts; in such case the effective D. C. voltage across each work-ring interface is the same, and all the rings CR^2, CR^3, CR^4 are held at the same potential and no inter-ring electrolytic etching action occurs. If the current flow across one work-ring interface were to be 40 amperes, across another 20 amperes, with no current flowing across the third, the voltage drops in the respective work-ring circuit resistors would then be 0.004

volt, 0.002 volt, and zero volts, and the potentials of the three conductive rings would differ from each other by these exceedingly small values, which are insufficient to cause detrimental inter-ring etching.

Accordingly, whether the conditions at the work-ring electrolytically-acting interfaces call for a more or less constant voltage control or regulation effected through the control windings W^3 of the pre-amplifier MA^1 or call for current limiting control under the dominating action of the control windings W^4 of the pre-amplifier MA^1, the maximum difference in potentials between any two conductive elements of the multi-faced wheel **110** cannot exceed the maximum signal voltage drop across any of the series resistances which are purposely made very small in ohmic value and in any of which the maximum current flow and hence the maximum value of D. C. signal voltage drop is automatically limited as above described, and thus detrimental inter-ring etching prevented. Moreover, it will be noted that when any work-ring interface calls for current limiting action, the voltage, illustratively 15.0 volts of the output of magnetic power amplifier MA^2, is reduced; that means a reduction of the voltage across the circuit **74—75** of Figure 8, thus, similarly reducing the voltage applied to all of the parallel circuits, in each of which is a work-ring interface and a series resistance, thus assuring that the maximum difference in potentials between conductive rings cannot exceed the maximum D. C. signal voltage drop, such as the 0.004 volts in the above illustration.

When we thus make it possible, because of the conversion of this small D. C. signal voltage to alternating potential and substantial amplification of the latter, to use low resistance values for the resistors R^{42}, R^{43}, R^{44} of Figure 8 or the resistor R^4 of Figure 7, we gain material advantages in the reduction of I^2R or heat losses, resulting in high efficiency. Even at 100 amperes, with a resistance of 0.0001 ohm, the I^2R loss is only 1 watt.

Aside from improved efficiency, the electrolytic grinding system of our invention achieves, it will now be seen, dependable self-accommodation to the variable or changing relationships between the work-piece and the conductive element (Figures 3, 5 and 7) or conductive elements (Figures 4, 6 and 8) of the grinding wheel as the "grinding" operation proceeds, and it does so under the control of the changing conditions at the work-wheel interface or interfaces, while at the same time achieving maximum stock removal capacity by electrolytic decomposition at the work-face, with or without abrasive action, commensurate with operational safety and protection of the rotating conductive element or elements against damage.

In these connections, dependable responses of the D. C. generating or conversion apparatus to changes in work-wheel interface conditions are reliably obtained by the coactions of the various parts above described, such as the illustrative rectifying, amplifying and other devices, including the preamplifier MA^1, whereby wide flexibility of adjustment and hence of operation may be had in order to adjust or set the system and apparatus to the requirements of any particular type of electrolytic grinding job that has to be done. For example, and to illustrate one type of adjustability of operation that may be had by the use of a saturable-core magnetic amplifier, we noted above that, in the preamplifier MA^1, the windings W^3 are active to maintain the voltage across the work-wheel interface or interfaces substantially constant so long as conditions thereat do not call for limitation of current thereacross, and in the illustrative circuit arrangement it was pointed out that, when interface conditions call for current limitation, windings W^4 of the magnetic amplifier MA^1 became energized to overcome the effect of the control windings W^3; that arrangement and description is to be interpreted as illustrative and not in a limiting sense in that the control windings W^4 and W^3 need not be connected to have opposing effects, as in the illustration, but can be connected to have additive effects so as to initiate and maintain current-limiting control of the power amplifier MA^2. Either action may be employed, depending upon the settings of the bias controls or of the biasing of the magnetic amplifier.

The energy conversion system under the control of the varying conditions at the electrolytically-acting work-wheel interface or interfaces will thus be seen to be thoroughly practical, efficient, and well adapted to meet the widely varying requirements and conditions of a wide variety of grinding operations; moreover, its features of achieving dependable self-protection lend it to facility and safety of use or operation by operators that need not be highly trained or skilled. It is readily and easily set or adjusted for different standards of control for substantial constancy of voltage and for different standards of current-limiting action, as by manually setting the reference voltage to the desired value and by making suitable manual adjustments in the converter-amplifier-rectifier circuit or circuits, such as setting grid-bias controls. Moreover, it will be seen that in the system and apparatus the several objects above noted, together with many thoroughly practical advantages, are successfully achieved.

As many possible embodiments may be made of the mechanical features of the above invention and as the art herein described might be varied in various parts, all without departing from the scope of the invention, it is to be understood that all matters hereinabove set forth, or shown in the accompanying drawings, is to be interpreted as illustrative and not in any limiting sense.

We claim:

1. In electrolytic grinding apparatus, in combination, a work-support and rotatable grinding wheel means having a plurality of conductive parts insulated from each other each part having a conductive face and with means mounting said work-support and said wheel means in coacting relation for operatively relating a workpiece supported by the work-support to the conductive faces of said conductive parts, means for supplying liquid electrolyte to the interfaces between the work-piece and said conductive faces for electrolytic decomposition at the work-piece face, a saturable-core magnetic amplifier having power winding means energizable by alternating current and having rectifier means in circuit therewith to provide unidirectional current at the output terminals thereof and having electro-magnetic means for changing the magnetic core saturation, a saturable-core control magnetic amplifier having power winding means energizable by alternating current and having rectifier means in circuit therewith to provide unidirectional current for energizing said electro-magnetic means of said first magnetic amplifier to control the latter and having control winding means for affecting its own core saturation, a plurality of supply circuits, one for each of said interfaces, extending from said output terminals by means connecting the positive side of said output terminals to the work-piece and by a plurality of means connecting the negative side thereof respectively to said conductive wheel faces and thereby forming a plurality of parallel electrolytic decomposition circuits, means comprising a rectifier bridge energized by alternating current and providing at its output a selectable unidirectional reference voltage, means dependent upon the voltage supplied to said supply circuits by said first-mentioned magnetic amplifier and upon said reference voltage for energizing said control winding means of said control magnetic amplifier and thereby affect said electro-magnetic means of said first-mentioned magnetic amplifier to maintain substantially constant the voltage at which the latter supplies current to said supply circuits whereby the respective current across said plurality of interfaces may vary relative to one another, a plurality of current-responsive means, one for each of said supply circuits and each responding to current flow in its associated interface of a selected maximum value such as a current value less than that which

causes detrimental arcing thereacross, and means interrelating said plurality of current-responsive means and said controlling winding means for affecting the energization of the latter and thereby control the output of said first amplifier responsively to any of said current-responsive means to effect limitation of the current flow across its corresponding interface to said maximum value and thereby impose substantially the same potential upon all of said conductive faces whereby to avoid or lessen material potential differences between conductive faces and avoid or lessen electrolytic action between them.

2. In electrolytic grinding apparatus, in combination, a work-support and rotatable grinding wheel means having a plurality of conductive parts insulated from each other each part having a conductive face and with means mounting said work-support and said wheel means in coacting relation for operatively relating a work-piece supported by the work-support to the conductive faces of said conductive parts, means for supplying liquid electrolyte to the interfaces between the work-piece and said conductive faces for electrolytic decomposition at the work-piece face, a saturable-core magnetic amplifier having power winding means energizable by alternating current and having rectifier means in circuit therewith to provide unidirectional current at the output terminals thereof and having electro-magnetic means for changing the magnetic core saturation, a saturable-core control magnetic amplifier having power winding means energizable by alternating current and having rectifier means in circuit therewith to provide unidirectional current for energizing said electro-magnetic means of said first magnetic amplifier to control the latter and having control winding means for affecting its own core saturation, a plurality of supply circuits, one for each of said interfaces, extending from said output terminals by means connecting the positive side of said output terminals to the work-piece and by a plurality of means connecting the negative side thereof respectively to said conductive wheel faces and thereby forming a plurality of parallel electrolytic decomposition circuits, means comprising a rectifier bridge energized by alternating current and providing at its output a selectable unidirectional reference voltage, means dependent upon the voltage supplied to said supply circuits by said first-mentioned magnetic amplifier and upon said reference voltage for energizing said control winding means of said control magnetic amplifier and thereby affect said electro-magnetic means of said first-mentioned magnetic amplifier to maintain substantially constant the voltage at which the latter supplies current to said supply circuits whereby the respective currents across said plurality of interfaces may vary relative to one another, a plurality of current-responsive means, one for each of said supply circuits and each responding to current flow in its associated interface of a selected maximum value such as a current value less than that which causes detrimental arcing thereacross, each of said current-responsive means having associated therewith means for converting its unidirectional response into amplified alternating current energy with means for rectifying the latter, said last-mentioned rectifying means having connections for unidirectionally energizing said control winding means whereby the latter respond to any of said current-responsive means to effect limitation of the current flow across its corresponding interface to said maximum value and thereby prevent potential differences between said conductive faces as would cause detrimental electrolytic action therebetween.

3. An electrolytic grinding apparatus as claimed in claim 2 in which said last-mentioned rectifying means has its output connected to said control winding means and each of the converting and implifying means respectively associated with said plurality of current-responsive means has its output connected to the input of said rectifying means whereby the latter responds to any of said converting and amplifying means.

4. An electrolytic grinding apparatus as claimed in claim 2 in which each of said converting and amplifying means comprises an electronic tube having grid electrode means provided with grid-bias control means for setting its cut-off point and thereby setting its response to correspond to the selected maximum current value in the interface associated with the corresponding current-responsive means, whereby the same maximum current value may be selected for all of said interfaces.

5. An electrolytic grinding apparatus as claimed in claim 2 in which said last-mentioned rectifying means comprises an electronic tube having grid means energized by alternating potential from said converting and amplifying means and has an output circuit for energizing said control winding means that comprises the secondary of a transformer of which the primary is energized by alternating current, and phase-control means for synchronizing and phasing the potentials effective on the grid means and in the output circuit.

6. In electrolytic grinding apparatus, in combination, a work-support and rotatable grinding wheel means having a plurality of conductive parts insulated from each other each part having a conductive face with means mounting said work-support and said wheel means in coacting relation for operatively relating a work-piece supported by the work-support to the conductive faces of said conductive parts, means for supplying liquid electrolyte to the interfaces between the work-piece and said conductive faces for electrolytic decomposition at the work-piece face, means for supplying unidirectional current to said interfaces comprising electromagnetic power winding means provided with saturable core means and energizable by alternating current and having rectifier means in circuit therewith to provide unidirectional current at the output terminals thereof, said core means having control windings for changing the magnetic saturation thereof, a plurality of supply circuits, one for each of said interfaces, comprising means connecting the positive side of said output terminals to the work-piece and a plurality of means connecting the negative side thereof respectively to said conductive wheel faces, means responsive to changes in voltage supplied from said output terminals to said supply circuits for affecting said saturation control windings to maintain said voltage substantially constant whereby the currents across said plurality of interfaces may vary relative to one another, a plurality of current-responsive means, one for each of said supply circuits and each responding to current flow in its associated interface of a selected maximum value such as a current value less than that which causes detrimental arcing thereacross, and means whereby said saturation control windings respond to any of said current-responsive means to limit the current flow across its corresponding interface to said maximum value and thereby cause said electro-magnetic power winding means and rectifier means to impress substantially the same potential, corresponding to the voltage accompanying said limited maximum current flow across said corresponding interface, upon all of said conductive faces of said grinding wheel means to prevent detrimental electrolytic action between them.

7. In electrolytic grinding apparatus, in combination, a work-support and rotatable grinding wheel means having a plurality of conductive parts insulated from each other each part having a conductive face with means mounting said work-support and said wheel means in coacting relation for operatively relating a work-piece supported by the work-support to the conductive faces of said conductive parts, means for supplying liquid electrolyte to the interfaces between the work-piece and said conductive faces for electrolytic decomposition at the work-piece face, means for supplying unidirectional current to said interfaces comprising electromagnetic

power winding means provided with saturable core means and energizable by alternating current and having rectifier meanas in circuit therewith to provide unidirectional current at the output terminals thereof, said core means having control windings for changing the magnetic saturation thereof, a plurality of supply circuits, one for each of said interfaces, comprising means connecting the positive side of said output terminals to the work-piece and a plurality of means connecting the negative side thereof respectively to said conductive wheel faces, a plurality of resistances, one for each of said supply circuits and serially arranged therein, for producing IR drops thereacross that are proportional to the respective currents across the interfaces, means supplying unidirectional current energization for said control windings, and means for controlling said last mentioned current-supply means to affect said control windings in direction to prevent increase in the potential at said output terminals and operating in response to the IR drop across any of said resistances reaching a selected value such as a value of current flow less than that which causes detrimental arcing and thereby prevent arc-over at the interface in the corresponding one of said plurality of circuits and thereby correspondingly limit the potential applied to the rest of said supply circuits, said resistances being of small ohmic values relative to differences in interface currents to provide IR drops insufficient to cause potential differences between said wheel conductive parts material enough to cause detrimental electrolytic action therebetween.

8. In electrolytic grinding apparatus, in combination, a work-support and rotatable grinding wheel means having a plurality of conductive parts insulated from each other each part having a conductive face with means mounting said work-support and said wheel means in coacting relation for operatively relating a work-piece supported by the work-support to the conductive faces of said conductive parts, means for supplying liquid electrolyte to the interfaces between the work-piece and said conductive faces for electrolytic decomposition at the work-piece face, means for supplying unidirectional current to said interfaces comprising electromagnetic power winding means provided with saturable core means and energizable by alternating current and having rectifier means in circuit therewith to provide unidirectional current at the output terminals thereof, said core means having control windings for changing the magnetic saturation thereof, a plurality of supply circuits, one for each of said interfaces, comprising means conneciting the positive side of said output terminals to the work-piece and a plurality of means connecting the negative side thereof respectively to said conductive wheel faces, said control windings comprising a winding having means for varying its energization in response to changes in voltage supplied to said supply circuits whereby the currents across said plurality of interfaces may vary relative to one another, a plurality of current-responsive means, one for each of said supply circuits, said control windings comprising winding means with means for energizing the latter under the control of any of said current-responsive means when the current flow across the associated interface approaches a selected value such as a current value that would cause detrimental arcing thereacross whereby to reduce the voltage applied to all of said interfaces and current flow across any of them beyond safe non-arcing value.

9. An electrolytic grinding apparatus as claimed in claim 8 in which said plurality of current-responsive means comprises a plurality of resistances arranged in series with the respective interfaces and of small ohmic values insufficient, for differing interface currents, to produce changes in the relative potentials of said wheel conductive parts for causing detrimental electrolytic action between the latter, and said means for energizing said second-mentioned control winding in response to

said current-responsive means comprising amplifying-energy supply means, one for each of said resistances and responsive respectively to the small IR drops thereacross.

10. In electrolytic grinding apparatus, in combination, rotatable grinding wheel means having a plurality of conductive parts insulated from each other with means for operatively presenting a work-piece thereto and with means for supplying liquid electrolyte to the interfaces between the work-piece and said conductive wheel parts, means for supplying unidirectional current at controllable voltage and current values to said interfaces and a plurality of supply circuits, one for each of said interfaces, comprising means connecting the positive side thereof to the work-piece and a plurality of means connecting the negative side thereof, each through a resistance, to said conductive wheel parts, means responsive to changes in voltage supplied said supply circuits for controlling said current-supply means to maintain the voltage thereof substantially constant whereby the currents across said plurality of interfaces may vary relative to one another, and means for controlling said current-supply means in response to a voltage drop across any of said resistances corresponding to the maximum desired current flow across its associated interface such as a current flow approaching in magnitude that which causes detrimental arcing thereacross to limit current flow across the corresponding interface to substantially said maximum value and thereby determine the reduced value of voltage applied across the others of said interfaces.

11. In electrolytic grinding apparatus, in combination, rotatable grinding wheel means having a plurality of conductive parts insulated from each other with means for operatively presenting a work-piece thereto and with means for supplying liquid electrolyte to the interfaces between the work-piece and said conductive wheel parts, means for supplying unidirectional current at controllable voltage and current values to said interfaces and a plurality of supply circuits, one for each of said interfaces, comprising means connecting the positive side thereof to the work-piece and a plurality of means connecting the negative side thereof to said conductive wheel parts, means associated with each of said supply circuits for producing a potential that is proportional to the current flow across the interface of its circuit without materially depreciating the voltage effective across the interface whereby to avoid potential differences between conductive wheel parts, when different current values flow across the interfaces, sufficient to cause detrimental electrolytic etching therebetween, and means operating upon said current-supply means in response to a potential produced by any of said potential-producing means corresponding to a selected value of current flow across the interface in its circuit for controlling the voltage at which said current-supply means furnishes current to all of said interfaces.

12. In electrolytic grinding apparatus, in combination, rotatable grinding wheel means having a conductive part with means including a work support for interrelating the conductive part and the work-piece for relative movement there-between whereby current-demanding conditions there-between may vary, such as changes in area or pressure of actual or apparent contact there-between, as relative movement between the work-piece and the face of said conductive part takes place for the purpose of shaping the work-piece by electrolytic decomposition and provided with means for supplying liquid electrolyte to the interface between the work-piece and said conductive wheel part for electrolytic decomposition at the work-piece face, a saturable-core magnetic amplifier having power winding means energizable by alternating current and having rectifier means in circuit therewith to provide unidirectional current at the output terminals thereof, means energizable by unidirectional current for changing the magnetic core saturation, means connecting

the positive side and the negative side of said output terminals respectively to the work-piece and to said wheel conductive part, a saturable-core control magnetic amplifier having power winding means energizable by alternating current and having rectifier means in circuit therewith to provide unidirectional current for energizing said electromagnetic means of said first magnetic amplifier and having control winding means for affecting its own core saturation, and means for controlling the energization of said control winding means to alter the unidirectional current energization of the electromagnetic means of said first magnetic amplifier to limit maximum current flow across said interface to a desired value such as a current value less than that which causes detrimental arcing and to maintain the voltage at said output terminals substantially constant for varying current flow across said interface at values less than said maximum value comprising means for affecting the energization of said control winding means and responsive to departures in voltage effective upon said interface from a standard of voltage at which current flow across the interface is less than said maximum value and means for affecting the energization of said control winding means in direction to depress the voltage at said output terminals and responsive to departures in upward direction of the current across said interface from said maximum current value.

13. In electrolytic grinding apparatus, in combination, rotatable grinding wheel means having a conductive part with means including a work support for interrelating the conductive part and the work-piece for relative movement there-between whereby current-demanding conditions there-between may vary, such as changes in area or pressure of actual or apparent contact there-between, as relative movement between the work-piece and the face of said conductive part takes place for the purpose of shaping the work-piece by electrolytic decomposition and provided with means for supplying liquid electrolyte to the interface between the work-piece and said conductive wheel part for electrolytic decomposition at the work-piece face, means for supplying unidirectional current to said interface comprising electromagnetic power winding means provided with saturable core means and energizable by alternating current and having rectifier means in circuit therewith to provide unidirectional current at the output terminals thereof, said core means having electromagnetic winding means for affecting the magnetic saturation thereof, means connecting the positive side and the negative side of said output terminals respectively to the work-piece and said wheel conductive part, means responsive to changes in voltage of said unidirectional current with means controlled thereby for affecting said saturation control winding means in direction to limit the effective voltage across said interface whereby the current thereacross may vary according to changing conditions at said interface, means responsive to current flow across said interface and acting when the current flow thereacross approaches arcing value and having means controlled thereby for affecting said saturation control winding means in direction to depress the output voltage of said current-supplying means and thereby prevent current flow from reaching arcing values, said voltage-responsive means and said means controlled thereby comprising means including a rectifier bridge energizable by alternating current and providing at its output a selectable unidirectional reference voltage with means dependent upon the voltage of the unidirectional current supply to the work-piece and upon said reference voltage for energizing said saturation control winding means with unidirectional current, said current-responsive means and said means controlled thereby comprising means for deriving an amplified alternating potential that is proportional to the current flowing across said interface with means including rectifier means for energizing said saturation control winding means with unidirectional current, said last-mentioned rectifying means comprising electronic tube means having grid means energized by said amplified alternating potential having an output circuit for energizing said saturation control winding means that comprises the secondary of a transformer of which the primary is energized by alternating current, and phase-control means for synchronizing and phasing the potentials effective on the grid means and in the output circuit.

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