May 22, 1956 G. E. COMSTOCK, 3D 2,746,917

ELECTROLYTIC GRINDING APPARATUS

Filed March 16, 1953 4 Sheets-Sheet 1

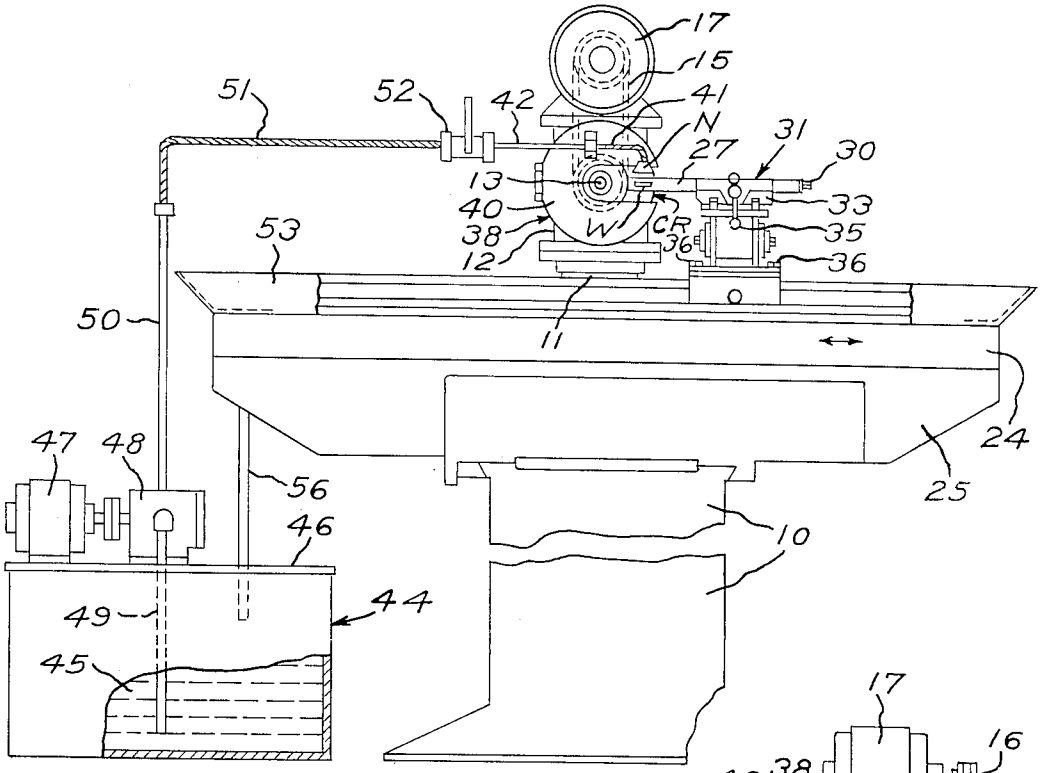


FIG. 1

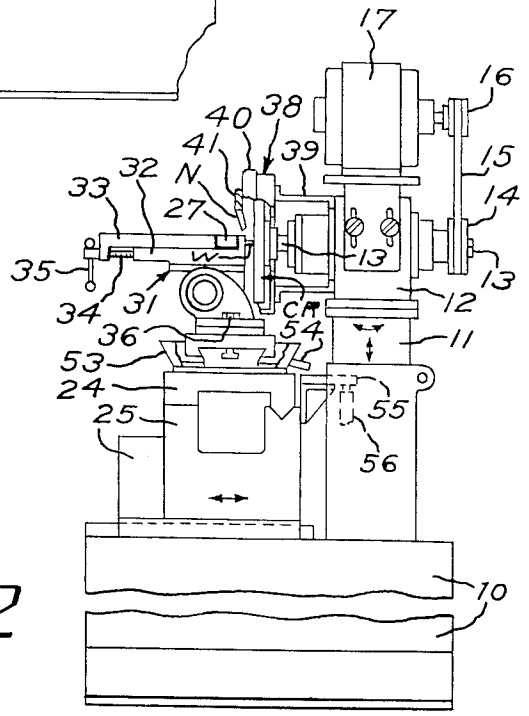


FIG. 2

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ELECTROLYTIC GRINDING APPARATUS

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FIG. 3

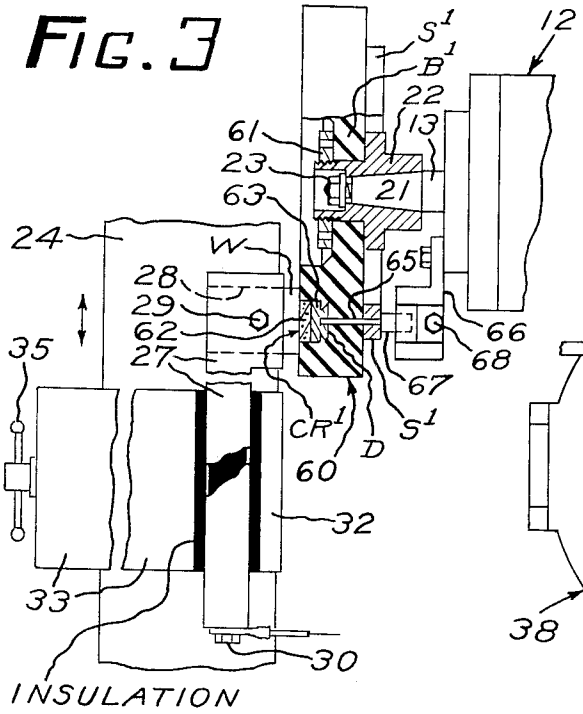
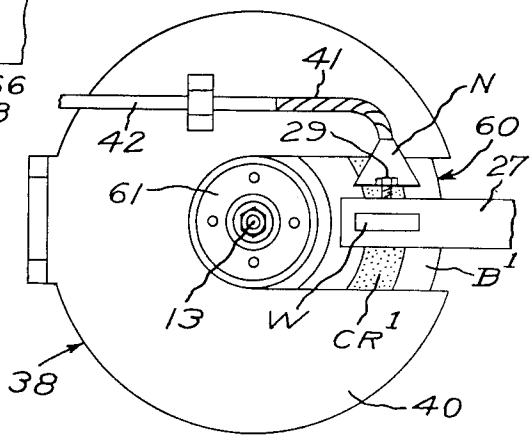


FIG. 5



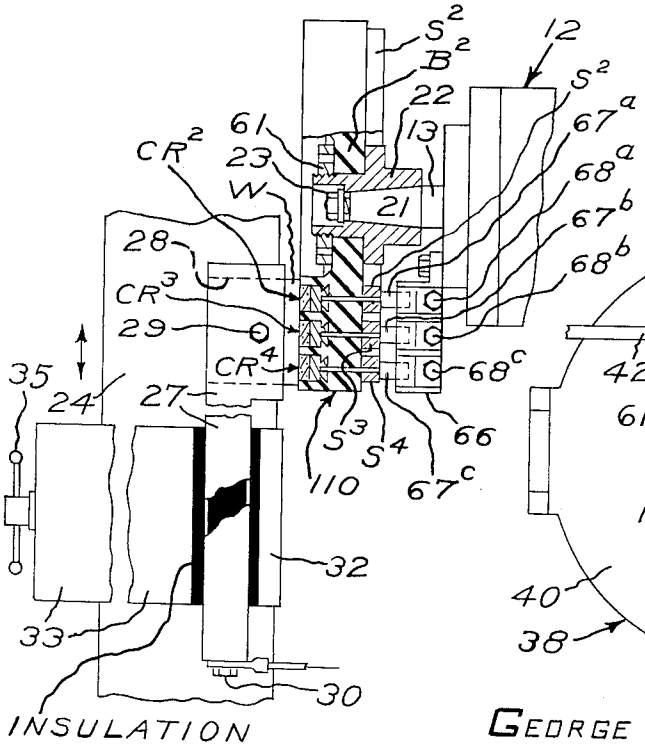


FIG. 6

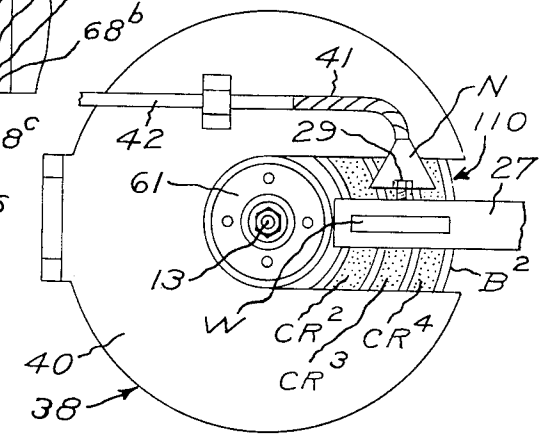


FIG. 4

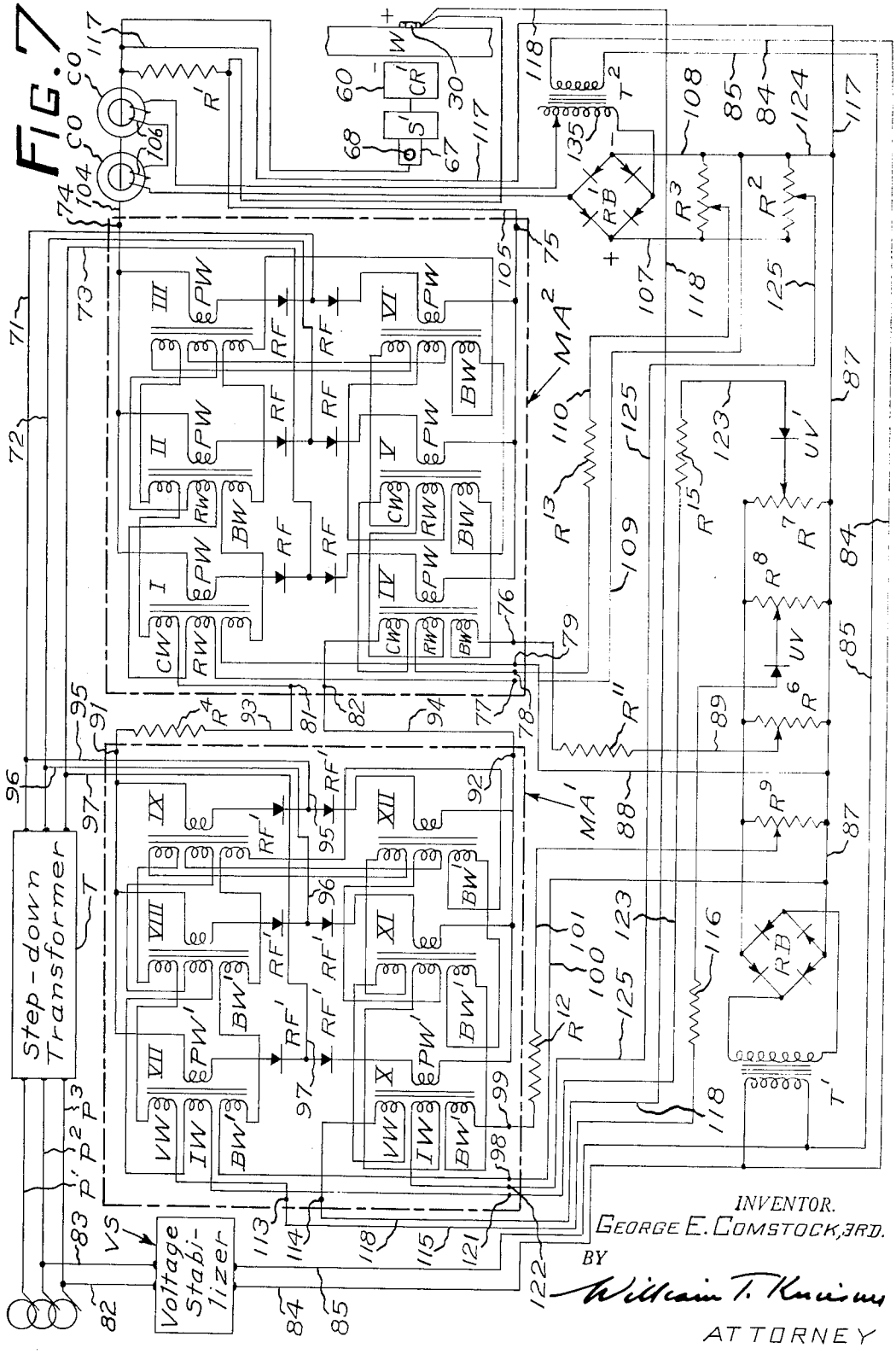
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ELECTROLYTIC GRINDING APPARATUS

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FIG. 7



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ELECTROLYTIC GRINDING APPARATUS

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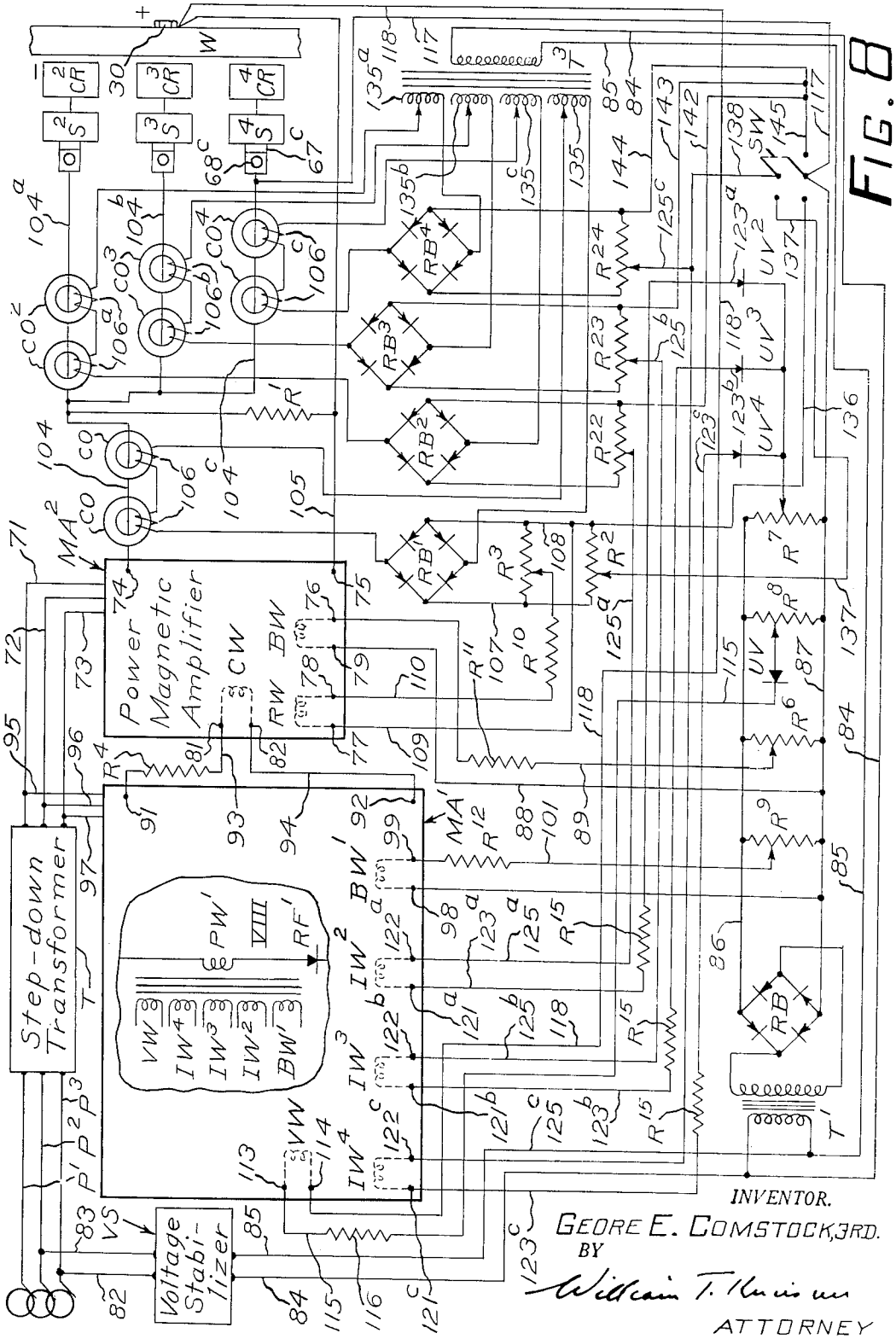


FIG. 8

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Patented May 22, 1956

2,746,917

ELECTROLYTIC GRINDING APPARATUS

George E. Comstock 3d, Holden, Mass., assignor to Norton Company, Worcester, Mass., a corporation of Massachusetts

Application March 16, 1953, Serial No. 342,373

17 Claims. (Cl. 204—218)

This invention relates to electrolytic grinding and more particularly to a system and apparatus for effecting stock removal electrically from a conductive work-piece face.

One of the objects of this invention is to provide a system and apparatus of the above-mentioned nature that is well adapted for ease and convenience of installation in factories or plants already provided with alternating current circuits or sources and that is of relatively simple control or regulation to effect efficient stock removal electrically under widely varying conditions of practical requirements and use. Another object is to provide, in a system and apparatus of the above-mentioned nature, controls of the flow or conversion of electrical energy for stock removal so as to provide, at the locus of electrical stock removal, voltage and current characteristics best suited for dependable, safe and efficient stock removal.

Another object is to provide a system and apparatus for effecting stock removal from a conductive work-piece by electrolytic decomposition at the work-piece face and to provide for dependable and flexible control of the conversion of alternating current energy to unidirectional or direct current energy at the locus of electrolytic decomposition in order to provide thereat voltage and current characteristics of the direct current energy best suited for efficient and safe stock removal. Another object is to provide a system and apparatus of the just-mentioned character in which the widely varying conditions at the locus of stock removal, caused by the exigencies or requirements met with in practice, effect control of the voltage and current characteristics, in a thoroughly dependable and quick-acting manner, of the direct current energy at the work-piece face so as to provide good safety and efficiency of operation. Another object is in general to provide an improved grinding apparatus and control system for electric stock removal at the work-piece face, in which circuit arrangements and controls are usable that can substantially lessen or avoid material heat losses.

Another object is to carry out the above-mentioned objects, severally or jointly, in which the apparatus and system effect reliable controls of the electrical energy at the work-piece face whether the therewith coacting conductive part of the apparatus consists of a single conductive element or comprises a plurality of conductive elements. Another object is to carry out the above-mentioned objects, severally or jointly, in which the apparatus and system, supplied initially from an alternating current source, effect, in a simple and dependable manner, 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 or without accompanying or concurrent abrasive action on the work-piece.

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 illustratively the mechanical and electrical features of my 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 workholder 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 workholder 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 3 and 6, and of the electrical energy supply system associated therewith and of the coacting controls therefor, certain corresponding parts which are shown in detail in Figure 7 being shown in diagrammatic representation thereof and certain parts being broken away to indicate diagrammatically and internally thereof certain modifications employed.

As conducive to a clearer understanding of certain features of my 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 my invention is to provide efficient and dependable electrolytic grinding apparatus and compact, simple, and coacting 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 or electrolytic action. As heretofore attempted to be practiced, so-called electrolytic grinding has encountered various difficulties or the sys-

tems 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 provide more flexible and more efficient controls, in response to changes in harmful direction of the electrical conditions at the locus of electrolytic decomposition of the work-piece, at greater stock removal capacity, of the conversion of the alternating current energy, whether or not electrolytic decomposition is accompanied by abrasive action.

In stock removal by electrolytic decomposition at the work face, the conductive work-piece is made the anode, and at the work-wheel interface, where there may or may not be physical contact and where there may or may not be accompanying abrasive action, there is adequately supplied a suitable electrolyte, which also serves as a coolant, and it is desirable to use high current density since the rate of electrolytic decomposition at the work-piece face is proportional to current flow. Various conditions can occur or be brought into being at the work-wheel interface that will cause detrimental actions, such as arcing, which can also cause high or excessive rates of wheel wear which, particularly where diamond abrasives are embodied in the wheel, can prove prohibitively costly. It can be shown that a desirable characteristic of supply of direct current for the electrolytic circuit is one where the voltage across the work-wheel interface is maintained substantially constant up to the point where the electrolytic current flow approaches a critical value above which deleterious arcing occurs, followed by current-limiting action at a selectable current value less than the critical current, to reduce the voltage across the work-wheel interface to prevent the current from reaching or exceeding the critical value. A further object of this invention is to effect conversion of alternating current electrical energy into direct current energy at the work-wheel interface with the energy conversion controlled, in response to conditions at the work-wheel interface so that the just described characteristic of energy supply at the work-wheel interface is provided in a simple, compact, efficient and reliable manner.

In describing my invention I 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 my 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, I 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, I 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 to 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, I 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 in so far 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 **10** 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 later to be described.

When the grinding wheel is so mounted at the front end of the spindle **13** it substantially overlies or overhangs a worktable **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 latter 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 my 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 suitable 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 I 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 discharge 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**.

The wheel CR may be of any suitable construction and may have one or more conductive faces, which I arrange to coact in effecting, in the electrical energy conversion and supply system, control or modification of the alternating current energy to provide direct current energy of the earlier above described characteristic of substantially constant voltage across the work-wheel interface followed by current limiting action with diminished voltage so that critical current values are not reached or exceeded. In one embodiment of my system and apparatus the wheel may have a single conductive face and illustratively, for that purpose, may be constructed as shown in Figures 3 and 5 about to be described in detail, while in another embodiment of my system and apparatus the wheel may have several conductive surfaces, such as three, as is illustratively shown in Figures 4 and 6 and illustratively constructed in a manner later described in greater detail.

Referring now to Figures 3 and 5, the single-conductive-faced wheel is there generally indicated by the reference character **60**, and 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 has molded into it a hole (Figure 3) so that it can be received onto the flanged 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 except 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 of 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 electrolytic grinding contain abrasive grains and the wheel 60 may be constructed 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 silicon carbide abrasive grains are hardly as effective on cemented carbides, while alumina grains grind them hardly at all. While, in the illustrative embodiments of my invention I 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 work-face without any matterial 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 described 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. I 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 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.

Any suitable metal bond appropriate for bonding the abrasive grains and for giving the rings suitable electrical conductivity may be used. 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, I 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 I 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 I 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 electrolytic 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 equi-angularly 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 I 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, I 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 I later described 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 rectangle 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 of 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 being respectively, as shown, between adjacent paired rectifiers RF—RF; direct current energy output is delivered at the output terminals 74, 75, leading from the interconnected power windings PW, as shown in Figure 7.

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 24 volts at an amperage on the order of 150 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, these aspects thereof 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.

However, the pecularities and variables that are virtually inherent in the actions or coactions that take place across the interface where stock removal from the work-piece W is electrically effected impose a number of difficulties and handicaps which work against simply connecting the D. C. output of the magnetic amplifier across the work-wheel interface, particularly if the desired precision of "grinding" and safety or protection for the wheel conductive element and the work-piece are also sought, and accordingly I have made readily adaptable provisions and relatively simple coacting circuit arrangements for dependably controlling the conversion of alternating current energy to electrical energy of voltage and current characteristics that are determined and controlled by the variables that occur at the work-wheel interface. These provisions and circuit arrangements will now be described.

In the illustrative embodiment I provide each of the six reactor units I, II, III, IV, V, VI with three control windings BW, RW, CW, which are energized in a manner later described to affect the saturable cores of the reactors. The windings BW of the several reactor units are connected for conjoint or simultaneous energization, as by connecting them in series as shown, their common circuit terminating at terminals 79, 76. In similar manner the several windings RW are interconnected, the resultant circuit terminating at terminals 77, 78. Windings CW are also in similar manner interconnected, with connecting terminals at 81, 82. Windings BW are bias windings which, when energized, bias the several reactor units in known manner, being energized by unidirectional current.

For this latter purpose and for other purposes later explained, I make suitable provision for deriving unidirectional current energy from the power line P^1, P^2, P^3. For example, from one of the phases of the three-phase power circuit I connect, as by conductors 82, 83, a voltage regulator or stabilizer VS, 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 be not reflected in the control circuits of the system; accordingly, conductors 84, 85 lead from the output side of the voltage stabilizer and provide a constant voltage circuit, from which relatively steady potentials may be provided and utilized.

Across the steady voltage circuit 84, 85 is connected the primary of a transformer T^1, whose secondary is connected as shown to the input terminals of a rectifier bridge RB, across the substantially constant voltage output terminals of which are connected conductors 86, 87, across which are bridged a number of resistors provided with taps so that the fixed voltage drop or constant unidirectional potential may be fractionalized or subdivided as required or needed. One of these resistors R^6 serves to energize the bias windings BW of magnetic amplifier MA^2 at the selected or desired potential derived from the fixed voltage across the output circuit 86, 87 of the rectifier bridge, in that a conductor 88, connected to one side of the resistor R^6 at conductor 87, leads to bias winding terminal 79, and another conductor 89 leads from the other connecting terminal 76 through a protective resistance R^{11} to the adjustable tap on resistor R^6. Accordingly, energization of the bias winding BW of the power magnetic amplifier MA^2 may be manually set by appropriately shifting the tap on resistor R^6.

The control windings CW of the power magnetic amplifier MA^2, having their connecting terminals at 81, 82, are preferably controllably energized under the control of a magnetic preamplifier MA^1, which has a unidirectional current output at terminals 91, 92, which are connected by conductors 93, 94, through a suitable resistor R^4, to the terminals 81, 82 of the control windings CW of the power amplifier MA^2; like the latter, the preamplifier MA^1 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 high permeability, with their respective output or power windings PW^1 interconnected with

rectifiers RF[1] as shown, the three-phase power line being connected by conductors 95, 96, 97 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 91, 92.

The preamplifier MA[1] is provided with bias windings BW[1], one for each reactor unit, and they are connected for conjoint or simultaneous energization as by connecting them in series as shown, with the common circuit terminating at terminals 98, 99. Unidirectional energizing current for the bias windings, of selectable or adjustable value, is derived from the constant voltage rectifier output circuit 86—87, across which is connected a resistor R^9 provided with a shiftable tap; a conductor 100 connects amplifier terminal 98, through circuit conductor 87, to one side of resistor R^9, and a conductor 101 connects the variable tap to the companion terminal 99 through a protective resistor R^{12}.

Means are provided for effecting coactions between the preamplifier MA[1] and the power amplifier MA[2], all under the control and direction of the peculiarly variable conditions at the work-wheel interface, for causing the electrical stock removal action at the latter to take place at maximum safe intensity; these include means for translating these electrical variables and include certain windings which I place on the reactors of the two amplifiers to respond thereto. To the D. C. output terminals 74, 75 of the power amplifier MA[2] I connect, by conductors 104, 105, the conductive wheel member CR[1] and the work-piece W, the latter being made anodic by connecting conductor 105 to the connector screw 30, and the connection of the negative output terminal 74 of the power amplifier to the conductive wheel member CR[1] being made by connecting conductor 104 to the connector screw 68 of the slipring brush 67.

Across the D. C. power output circuit 104, 105 I connect a resistor R^1, illustratively of about 3 ohms; resistor R^1 provides a small load on the D. C. output side of the power amplifier MA[2] 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. An illustrative interface voltage for this purpose may be, say, 10 volts.

Various factors and variables at the interface can cause departures from the desired or most suitable values of D. C. voltage across the work-wheel interface and of the current flowing thereacross for stock removal from the work-piece W. Changes in applied voltage can be conveniently measured by the voltage across the small-load resistance R^1 in which they are reflected; certain voltage changes I make operative to affect preferably the preamplifier MA[1] in a manner later described. As for changes in current across the interface, I make provision for causing certain responses thereto to take place preferably in both the power amplifier MA[2] and in the preamplifier MA[1]; in this latter connection I employ one or more interface-current-responsive devices, each preferably in the form of a core CO that extends about or envelops one of the conductors, such as conductor 104, that lead to the conductive wheel element CR[1] and work-piece W, the core CO having thereon a winding 106. The core CO may be of any suitable construction or arrangement, preferably and illustratively it is torus-shaped, and it is made of transformer iron or steel of suitable permeability. The magnetic field produced by the current flowing in conductor 104 extends circularly about the conductor, being coaxial therewith, and with the torus-shaped iron core CO positioned coaxially with the conductor 104, the core forms a high-permeability path for the flux and the flux density in the core varies with the magnitude of the current flowing through the conductor. The parts are so proportioned in relation to the current magnitudes that, as the interface calls for increasing current, the core moves closer and closer to saturation on its permeability curve. The action of the winding 106 can in this manner be affected or varied according as interface current flow changes in magnitude.

Winding 106 is energized in an alternating current circuit and hence the just-described action of the core affects and changes the impedance of the winding 106.

I provide a transformer T[2], of which the primary is energized from the steady or constant voltage circuit 84, 85 above described, and of which the secondary is connected in series with the winding 106 across the input terminals, as shown, of a rectifier bridge RB[1], across the output terminals of which are connected conductors 107, 108, across which, in turn, are bridged resistors R^2, R^3; the latter are thus energized by unidirectional current resulting from the full-wave rectification of the rectifier bridge and at a voltage which changes as the voltage across the input terminals of the bridge is changed by changes in impedance of the winding 106.

Resistor R^3 is provided with a shiftable tap so that any desired fraction of the variable voltage thereacross may be made available, and such a selected unidirectional potential I utilize to energize the control windings RW of the power magnetic amplifier MA[2]. More particularly, a conductor 109 connects the amplifier terminal 77 to one end of resistor R^3 by way of conductor 108, and a conductor 110 connects the other terminal 78 of the windings RW to the shiftable tap of the resistor R^3, through a protective resistance R^{13}, as shown in Figure 7.

The windings RW of the power amplifier MA[2] are thus steadily energized by unidirectional current, but the effect of the windings RW on the respective reactor units of the power amplifier MA[2] and upon the output of the latter is under the control of the current flowing across the work-wheel interface, and in accordance with certain other features of my invention, later described, other controls are made to coact therewith for purposes later described. Varying conditions at the work-wheel interface can and do call for substantial changes in current flow thereacross. For example, at one point in a stock-removal operation, as, for example, when the actual or apparent contact between the work and the wheel is of relatively high resistance, current flow across the interface may be small, but as that resistance is decreased, as by bringing about more intimate contact or increased pressure of contact, current flow substantially correspondingly increases. With resultant increase in current output of the power amplifier MA[2], the output voltage of the latter across the output terminals 74, 75 falls off or declines, causing a drop in the energy dissipated at the work-piece face and loss in rate of stock removal. At low values of interface current, unidirectional flux in the core CO is correspondingly low and the impedance of winding 106 is high so that there is a relatively high reactance drop in the secondary output circuit of transformer T[2] and the alternating potential applied to the input of the rectifier bridge RB[1] is correspondingly low; accordingly, the unidirectional voltage across the rectifier output circuit 107, 108 is low and the energization of windings RW of the power amplifier, derived from the resistor R^3, is also low. When, however, the work-wheel interface calls for increased current flow thereacross the current of the increasing current flow increases the unidirectional flux in the core CO, driving the latter more and more toward saturation and thereby correspondingly lessening the impedance of winding 106 and the impedance drop thereacross so that more and more of the alternating voltage of the secondary of transformer T[2] is effective at the input terminals of the rectifier bridge RB[1]; correspond-

ingly, the unidirectional output voltage of the rectifier bridge and the voltage across resistor R^3 are increased, as is also the unidirectional energization of the windings RW of the power amplifier. The increasing energization of windings RW affects the cores of the reactor units of the power amplifier in directions to cause the unidirectional voltage at its output terminals **74**, **75** to increase as against the inherent drop in output voltage that would otherwise take place. With the resultant compensation for decline in output voltage of the power amplifier, the call for increase in interface current as required by the changed or changing conditions at the interface can be and is satisfied and loss in rate of stock removal avoided.

The arrangement just described has many advantages from the viewpoint of structural elements involved in that the latter, such as the variable impedance device comprising the winding **106** and core CO, the transformer T^2, the full-wave rectifier bridge RB^1 and tapped resistor R^3, are relatively simple in construction, and the accompanying circuit arrangements are also relatively simple, all as will now be seen; moreover, these parts, when interrelated as above described, with each other and with the work-wheel interface achieve numerous practical advantages of coaction and operation; for example, varying or changing conditions at the work-wheel interface effect dependable and substantially proportionate responses to current changes across the interface and do so without material loss or wastage of energy flowing across the interface, and it is possible to avoid substantial heat losses in that one need not employ a series resistor in the work-wheel interface circuit. Also, these responses are efficiently translated into proportionate values of voltage or current or both, such as the unidirectional potential across the rectifier output circuit **107**, **108**, which are of a magnitude appropriate or suitable for directly energizing control windings of the magnetic amplifier or amplifiers employed. In the above described embodiment the windings RW of the amplifier MA^2 will be seen to be directly energized from this circuit **107**, **108**, and this takes place at variable voltage and current of magnitudes suited to the construction of the power amplifier. For setting or changing the standard of operation for compensation of voltage drop in the output of the power amplifier, the variable tap at the resistor R^3 may be appropriately set. Also, the secondary winding of transformer T^2 may be provided with a tap as shown, for similar purposes. Either or both may be set, according to the range of change in standard of operation to be effected.

Coacting with the above, as above indicated, are other features, also under the dictation or control of the peculiarly varying conditions at the locus of electrical stock removal from the work-piece face. Among other control windings, preferably applied to the magnetic preamplifier MA^1, are windings VW, one for each of the reactor units VII, VIII, IX, X, XI, XII and suitably connected, illustratively in series as shown, for conjoint or simultaneous energization, from the amplifier terminals **113**, **114**, whereby the windings VW, in coaction with the bias windings BW^1, may be connected, as is about to be described, to achieve certain controls over the voltage which the power amplifier MA^2 applies to the work-wheel interface. Across the substantially steady or constant voltage circuit **86**, **87** earlier above described I provide a resistor R^8 that has a tap as shown, by which any portion of the voltage across the resistor R^8 may be selected as a fixed or steady reference voltage against which to measure the voltage across the work-wheel interface, a voltage which can change substantially according to various factors including changing conditions at the work-wheel interface.

These two voltages, that is, the selected reference voltage tapped from resistor R^8, and the voltage across the work-wheel interface W—CR^1, I bring into coaction to control the energization of the preamplifier windings VW, in a circuit which extends from preamplifier terminal **113**, then conductor **115**, a protective resistor **116**, a unilateral valve or rectifier UV, resistor tap, then the selected portion of resistor R^8, conductor **87**, conductor **117**, and by brush **67** and slipring S^1, to the conductive wheel element CR^1, which is one side of the work-wheel interface, and from the work-piece W, which is the other side of the work-wheel interface, by way of conductor **118**, to the other preamplifier terminal **114**. In this circuit arrangement, as will be seen by the just described circuit connections, the reference voltage set or selected by the tap on resistor R^8 and the voltage across the work-wheel interface, both unidirectional, are in opposition to each other. So long as the voltage across the interface is less than the selected reference voltage at resistor R^8, so that the fixed reference voltage determines the direction in which current flow would take place in the described series circuit, which includes the preamplifier windings VW, current flow to and through the windings VW need not take place, for there need not be any interference with the self-control which the work-wheel interface conditions can variably effect through the windings RW of the power amplifier MA^2 as earlier above described, and accordingly the unilateral valve or rectifier UV is included in the circuit to block current flow to the preamplifier windings VW.

The bias windings BW^1 of the preamplifier are energized, by setting the tap on resistor R^9, so that with no current flowing in the control windings VW the preamplifier MA^1 is biased, and stands biased, at or just below cut-off, so that the preamplifier has a zero output and hence control windings CW of power amplifier M^2 are, and stand, de-energized. The bias windings BW of the power amplifier, by adjustment of the tap at resistor R^6, are energized at a value to bias the amplifier above cut-off to provide unidirectional output, to the work-wheel interface, at the desired voltage which, should it inherently fall off because of increase in interface current, the latter effects compensation for the voltage decline by increasing the energization of windings RW in a direction to increase the bias and thus correspondingly raise and substantially restore the voltage across the work-wheel interface.

However, should the voltage across the work-wheel interface exceed that of the selected reference voltage at resistor R^8 so that the resultant difference in voltage determines flow of current in reverse direction, the rectifier UV permits such flow to take place and the preamplifier control windings VW are energized. The resultant energization of windings VW, in relation to the cut-off bias effect of bias windings BW^1, biases the reactor units above cut-off and causes a current flow at the D. C. output of the preamplifier at its terminals **91**, **92** which are connected to the control windings CW of the power amplifier MA^2. As a result windings CW are energized in direction and amount to bias power amplifier toward cut-off so that the output voltage at terminals **74**, **75** of the power amplifier MA^2 is reduced and prevented from materially exceeding the selected reference voltage at resistor R^8.

I am thus enabled to select, for any particular kind or type of grinding job, a suitable or thereto appropriate voltage to apply across the locus of electric stock removal from the work-piece, a voltage which, for electrolytic decomposition at the work-face, may be on the order of 10 volts or 15 volts, or more, up to about 30 volts, and to maintain or regulate it for substantial constancy, under control of the varying conditions at the work-wheel interface. For example, should effective conduction be broken, as by moving the work-piece completely out of relation to the conductive element of the apparatus, as in offhand grinding, or should the apparatus stand idle while a work-piece is being removed for replacement, the windings RW of the power amplifier stand substantially de-energized and the voltage across the amplifier output terminal **74**, **75**, to which the small-load resistance R^1 is permanently connected, stands at the selected value as determined by the setting, at resistor R^6, of the energizing current for the bias windings BW. The work-piece may thus be safely brought into conductive relation, and thereafter changes

in interface conditions determine the coaction of the above described parts, such as the energization of power amplifier windings RW to compensate for voltage decline and to maintain good rate of stock removal so long as the selected interface voltage is not exceeded and to bring into action the preamplifier windings VW to effect energization of the power amplifier windings CW to guard against the interface calling for and receiving thereacross voltage in excess of the selected and appropriate value. However, and particularly in effecting stock removal by electrolytic decomposition, it is desirable to make provision against permitting interface conditions to call for and receive magnitudes or densities of current as are damaging to the apparatus; for example, in electrolytic grinding, arc-over, which can be caused in the manner earlier above indicated, can be destructive to the conductive element or elements of the grinding wheel, and such destructive action can be especially costly where the conductive element is expensive to manufacture or where it contains costly diamond abrasive grains.

Accordingly, I provide the preamplifier MA^1 with control windings IW, one for each of the reactor units VII, VIII, IX, X, XI, XII, which, as shown in Figure 7, are interconnected, illustratively in series, for conjoint or simultaneous energization, their circuit terminating at connecting terminals **121**, **122**. These I arrange so that they will respond to interface conditions that call for current flow thereacross in excess of a selected safe maximum current value which can be just below the current value at which harmful or damaging arcing would occur. For example, for one type of grinding job the critical arcing current value may be 40 amperes, and in such case it may be desired to limit current rise across the work-wheel interface to a value of, say, 30 amperes, thus also providing an ample margin of safety.

Across the fixed or steady unidirectional voltage circuit **86**, **87**, I bridge a resistor R^7 and provide it with a tap as shown so that any fraction of the voltage drop across the resistance may be selected as a standard against which to measure changes in interface current; by the structural elements and circuit arrangements above described, including the saturable impedance device **106**–CO, the transformer T^2 and the rectifier bridge RB^1, current changes across the interface W–CR^1 are translated into a substantially proportionately varying unidirectional voltage across the circuit **107**, **108**, and across the latter I bridge a resistor R^2, which I also provide with a tap as shown, so that any selected fractional part of the voltage drop thereacross may be utilized.

These resistors R^7, R^2, with their respective taps, I arrange in circuit with the preamplifier windings IW in such manner that the resistor potential drops are in opposition to each other. This circuit extends from preamplifier terminal **121**, then by conductor **123**, through a protective resistor R^{15}, through a unidirectional valve or rectifier UV^1, through the resistor tap and the selected portion of the resistor R^7, conductor **87**, conductor **124**, selected portion of resistor R^2 and its tap, and then by conductor **125**, to the other preamplifier terminal **122**.

The settings or adjustments, as by setting the tap on resistor R^7 and the top on resistor R^2, are so made that the selected fixed or steady voltage across the selected portion of resistor R^7 is equal to the voltage across the selected portion of resistor R^2 when the current across the interface equals the selected safe value which is not to be materially exceeded, illustratively 30 amperes where the critical or destructive arcing current is 40 amperes, as assumed in the above given illustration. Accordingly, so long as the interface current is at or below the safe maximum value, the voltage drop at resistor R^2, which is proportional to the interface current, is equal to or less than the reference voltage drop provided by resistor R^7; these voltages are in opposite directions in the series circuit of the preamplifier windings IW, and no current flows through the latter so long as the reference voltage at resistor R^7 preponderates over the current-responsive voltage drop at resistor R^2, because the unidirectional valve UV^1 stops or blocks current flow in that direction. So long as these conditions exist, varying or changing interface conditions can call upon and effect, by the arrangements earlier above described, actuation of the power amplifier windings RW to compensate for declining voltage or to call upon and energize the voltage-responsive windings BW of the preamplifier in turn to energize the control windings CW of the power amplifier to maintain the work-wheel voltage substantially constant or to prevent excessive rise in that voltage.

As soon, however, as an interface condition arises calling for more than the selected safe maximum current value such as the above-mentioned 30 amperes, and such a condition can illustratively arise as by a substantial increase in interface area or substantial and sometimes sudden increase in pressure between the work and wheel, the current-responsive voltage drop across the selected portion of resistor R^2 exceeds the reference voltage drop at resistor R^7, and with the former preponderant, current can now flow through the preamplifier current-responsive windings IW, for the direction of flow is the same as that permitted by the valve or rectifier UV^1, in the above described series circuit, which includes the windings IW. Accordingly, the bias of the reactor units of the preamplifier MA^1 is changed to permit or cause current flow at its output terminals **91**, **92** to the control windings CW of the power amplifier MA^2 in a direction and amount to bias the power amplifier downwardly toward cut-off and thus hold the current output of the latter and the current across the interface against materially exceeding the selected safe value.

In this manner the very condition at the work-wheel interface that would otherwise bring about undesired or damaging action is made to effect controls to safeguard itself against an undesired or destructive action. Thus the critical or damaging current value of 40 amperes in the above illustration is prevented from coming into being. Electrolytic grinding may, therefore, proceed safely in spite of many variables that can be introduced by not only various types of grinding operations but also by varying conditions accompanying any particular type of grinding operation. For example, there may be relative traverse between grinding wheel and the work-carrying table **24** (Figures 1, 2 and 3), as by longitudinal movement of reciprocation of the table, 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, 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, changes in pressure of contact, or the like, may take place. Or, where the work W is manually manipulated, as in offhand 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 this invention successfully copes, as above described.

According to certain other features of our invention, and in order to achieve still further practical advantages, I 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 slip-ring, 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 6, 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 work-piece 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, I again provide a saturable magnetic amplifier, which may be similar to the magnetic amplifier MA^2 and which I have therefore represented, in Figure 8, as a whole, by the rectangle marked MA^2, with the connecting terminals as described in connection with Figure 1, also indicated, and with the several sets of series-connected control windings diagrammatically indicated as a whole and designated by their respective reference characters BW, RW, CW; as in Figure 7, the power amplifier is connected through the transformer T 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 at the D. C. output terminals **74**, **75**, to one of which workpiece W is connected by conductor **105** at the connector screw **30** so that the work is anodic, and to the other of which the conductive abrasive rings CR^2, CR^3, CR^4 are connected by conductor **104** and branch conductors 104^a, 104^b, 104^c to 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.

With multiple conductive elements on the rotating wheel **110** it is possible to materially increase the capacity for electrolytic stock removal in that materially higher total current flow and higher current density may be used, and in accordance with my invention dependable protection also achieved against detrimental or destructive arcing, or like undesired effects. For example, in the illustrative embodiment of Figures 4, 6 and 8 with three conductive wheel elements CR^2, CR^3, CR^4 juxtaposed to work W, and again assuming that the critical arcing current value is 40 amperes, I am enabled to provide for the flow of a maximum safe current of 30 amperes across each electrolytically acting interface so that electric stock removal proceeds at a 90-ampere rate and the capacity of the apparatus is trebled; by further increasing the number of conductive elements in the wheel, still greater increase in capacity can be obtained. My invention provides a system and apparatus of substantial flexibility or wide adaptability to achieve dependable, safe and efficient operation under the control of the variable work-wheel interface conditions, so that increase in stock removal capacity as just mentioned, with greatly increased production, may be effectively achieved, as will be illustratively pointed out in describing the illustrative system and apparatus of Figure 8.

For the above-described multiplied or increased current output, illustratively 90 amperes, the power amplifier MA^2 is correspondingly adjusted, as by adjusting the tap at resistor R^6 in order correspondingly to shift the biasing energization of the bias windings BW which, as in Figure 7, are connected by conductors **88**, **89** which extend from the connecting terminals **79**, **76** to the selected portion of resistor R^6 which is bridged across the D. C. constant voltage circuit **86**, **87**; since the voltage of the D. C. output of power amplifier MA^2 will now be somewhat higher, for example 20 volts, the tap on resistor R^8 is appropriately shifted to increase the value of the reference voltage against which the voltage across the parallel work-wheel interfaces (when the work W is related to the conductive wheel elements) and the voltage across the resistor R^1 (when the work-wheel interfaces are open-circuited, as by removing the work W therefrom) is to be measured in order to determine the action of the voltage-responsive field winding VW of the preamplifier MA^1 for effecting substantially constant voltage regulation by the action of the control windings CW of the power amplifier MA^2 in biasing the latter downwardly in opposition to the upward biasing action of the windings BW and RW.

The just-mentioned voltage control circuit, as in Figure 7, has included therein, in opposition to each other, the selected reference voltage across a portion of resistor R^8 and the voltage across the parallel interfaces or across the resistor R^1, and the circuit extends from terminal **113** of the series-connected control windings VW of preamplifier MA^1, then conductor **115**, protective resistance **116**, valve or rectifier UV, the resistor tap, a portion of resistor R^8, conductor **87**, conductor **117**, then to branch conductor 104^c or brush connector 68^c, then to one side of resistor R^1 which has in parallel with it the parallel interfaces, then from the other side of the resistor R^1 and the work-piece W (at connector screw **30**) by way of conductor **118** to the other preamplifier terminal **114** of the control windings VW. As in Figure 7, so long as the interface voltage or, upon open-circuiting of the several interfaces, the voltage across the resistor R^1 is less than the reference voltage at resistor R^8, flow of current to the voltage-responsive windings VW is blocked by the rectifier valve UV and windings VW remain unenergized, but as soon as conditions arise to cause the selected reference voltage at resistor R^8 to be exceeded energizing current flows through the preamplifier windings VW in direction permitted by the rectifier UV and voltage regulation across the parallel interfaces and across the resistor R^1 proceeds in a manner above described and that will now be clear.

To compensate for declining voltage of the output of the power amplifier MA^2 that accompanies increasing current demand made by the parallel interfaces, the power amplifier MA^2 is again provided with the windings RW, and these I again arrange to be energized, at the connecting terminals **77**, **78** thereof, through conductors **109**, **110**, from a selectable portion of the resistor R^3 which is

bridged across the circuit 107, 108 that is unidirectionally energized at the output terminals of the rectifier bridge RB^1 at a voltage which, as in Figure 7, is proportional to the current demanded by the interface; where several interfaces are provided in parallel, as in Figure 8, and since it is the sum total of current called for by the several parallel interfaces that effects voltage decline upon increasing demand, one or more torus-shaped cores CO with windings 106 thereon are magnetically and coaxially related to the conductor 104 through which this total current, as called for by several interfaces, flows. The input side of the rectifier bridge RB^1 is energized from the secondary winding 135 of a transformer T^3, which corresponds to the transformer T^2 of Figure 7 and which has its primary winding connected by conductors 84, 85 to the steady voltage output of the voltage stabilizer VS; the alternating energizing current that flows to the rectifier bridge RB^1 passes through the winding or windings 106, and as is now clear in view of the description of Figure 7 the impedance of the cored windings 106 varies substantially in inverse proportion with the current flowing through conductor 104, being the sum total of the several currents respectively called for by the several interfaces according to whatever conditions exist thereat.

Accordingly, the D. C. voltage across the rectifier output circuit 107—108 and hence across the selected portion of resistor R^3 varies substantially directly as the total current flow to the several interfaces, and as the latter call for more and more current the energization of the winding RW of the power amplifier MA^2 increases substantially correspondingly so as to bias the amplifier in a direction to increase its output voltage sufficiently to compensate for the otherwise inherent decline in output voltage as its current output increases. Thus, at the several interfaces, full capacity of electric stock removal from the work-piece, for any given interface condition, is achieved and decline in productive capacity of the apparatus counteracted.

In this manner, it will now be clear, compensation for decline in voltage can be effectively achieved as the several interfaces call for more current; but provision is made to regulate against excessive current flow across the interfaces such as would cause destructive or other detrimental action, and such provision may be flexibly effected according to desire or according to the particular type of grinding operation being performed.

In the illustration given above, it may be assumed that the safe maximum total current flow which the several interfaces may demand is 90 amperes and that it is desired that that amount of current is not to be exceeded, lest it bring about destructive action at the interfaces. Assuming that a grinding job is being performed in which conditions at the several interfaces, that is, in Figure 8 between the conductive element CR^2 and the work W, between element CR^3 and the work W, and the element CR^4 and the work W, are not subject to wide differences from each other so that the three interfaces substantially equally divide the total current between them. In that case I bridge across the variable D. C. voltage circuit 107, 108 a resistor R^2, like the resistor R^2 of Figure 7, and provide it with a tap so that any portion of the voltage drop thereacross may be selected, and the resultant D. C. voltage, which varies substantially directly with the total current flow to the interfaces, I bring into coacting relation with a resistor R^7 across the constant voltage circuit 86, 87 to control, preferably through a rectifier or valve, the energization of a winding in the preamplifier MA^1, like the winding IW of the preamplifier MA^1 of Figure 7. For purposes later explained, the preamplifier MA^1 of Figure 8 is provided with several of these windings on each of the reactor units VII, VIII, IX, X, XI, XII, being in number the same as the number of work-wheel interfaces employed, illustratively three as in the illustrative embodiment of Figure 8.

In Figure 8 there is a broken-away area corresponding to the reactor unit VIII in order there to show how all of the reactor units are provided not only each with a voltage-responsive winding VW and a bias winding BW^1, but also with three current-responsive windings IW^2, IW^3, IW^4, which are connected and allocated, as is later described, respectively to the three interfaces at the conductive wheel elements CR^2, CR^3, CR^4. The respective current-responsive windings of the several reactors of the preamplifier MA^1 are connected in respective series circuits, and in Figure 8 the resultant three series-connected sets of windings are diagrammatically indicated and identified each as a whole by the reference characters IW^2, IW^3, IW^4. It is one of these that I bring into coaction with the tapped resistor R^2, and for convenience, let it be the series current-responsive windings IW^4.

Accordingly and illustratively, and in order to provide ready adaptability to other grinding conditions, I first provide a double-bladed double-throw switch SW connected into the circuits substantially as shown in Figure 8. To one fixed contact at the left I connect by conductor 136 one end of the resistor R^2, and by conductor 137 I connect the tap of the resistor R^2 to the other fixed contact at the left. Conductor 87 of the fixed voltage circuit 86, 87 is connected to one switch blade, as is also the above-described conductor 117, and to the other switch blade, by conductor 138, connection is made to conductor 125^c which extends to connecting terminal 122^c, to which one side of the series-connected current-responsive windings IW^4 is internally connected, and from the other connecting terminal 121^c thereof a conductor 123^c extends, with an interposed protective resistor R^{15}, through a unidirectional valve or rectifier UV^4, to the tap on the resistor R^7, this circuit being closed when the switch SW is thrown to the left so as to include in series therewith the selected portion of the resistor R^2 with the voltage drop thereacross acting in a direction opposite to that of the selected reference voltage at resistor R^7.

Appropriate adjustments, as at the taps of resistors R^2 and R^7, are made so that, with the selected safe maximum value of current flowing to the several interfaces, illustratively 90 amperes, the voltage drop across the selected portion of resistor R^2 is equal to the reference voltage across resistor R^7 with such adjustment made, so long as the several interfaces do not call for a total current in excess of 90 amperes, the reference voltage across resistor R^2 is preponderant, in the series circuit of the windings IW, over the current-responsive voltage drop at resistor R^2, but current flow through the windings IW^4 is stopped or blocked at the valve UV^4. When the total current called for by the interface causes the voltage drop at resistor R^2 to exceed the fixed reference voltage across resistor R^7, the resultant potential difference in the series circuit of the current-responsive windings IW^4 is in reverse direction and current flow to the windings IW is permitted in that direction by the valve UV^4. The resultant energization of the windings IW^4 shifts the magnetization of the cores of the reactors of preamplifier MA^1 to cause current flow in direction and amount to energize the control windings CW of the power amplifier MA^2 so that the windings CW oppose the action of windings RW and BW and thus prevent the total current flow to the several interfaces from materially exceeding the selected maximum value, illustratively 90 amperes.

However, there are grinding jobs or conditions of stock removal from the work-piece W of such a nature that conditions at the several interfaces are not always such as bring about substantial equality of division of the total current between the several interfaces. For example, the work W may be traversed or shifted so that actual or apparent contact is with less than all of the conductive wheel elements CR^2, CR^3, CR^4, or by way of further example, actual spacings at the several interfaces or actual pressures of contact may be widely different at the several conductive elements. While the maximum safe total current

is not exceeded in the above-described arrangement, the total current is divided amongst the several interfaces according to the dictates of the respectively different conditions existing thereat, and again assuming as in the above given illustration that in electrolytic grinding the critical spark-over current is 40 amperes, it is possible that that value may be reached or exceeded at one or more of the several interfaces. Also, were the work W to be reciprocated or traversed lengthwise relative to the conductive wheel elements and virtually run off of them, the work W finds itself juxtaposed to all three wheel elements CR^2, CR^3, CR^4 at one point in its stroke, at another point it finds itself juxtaposed to only two of them, at a subsequent point it is juxtaposed to only one of them, and a circumstance like this can give rise to damaging current flow, as is now apparent.

I therefore make provision for guarding against damaging unequal division of the total current flow amongst the several interfaces, and an illustrative arrangement is shown in Figure 8. With each of the branch conductors **104a**, **104b**, **104c** that lead to the respective interfaces I associate magnetically and coaxially therewith one or more torus-shaped core members as shown at CO^2, CO^3, CO^4 respectively, with respective windings **106a**, **106b**, **106c** thereon to form variable impedance units of the kind above described and explained in greater detail in connection with Figure 7. For each I also provide full-wave rectifying bridges RB^2, RB^3, RB^4, having their respective A. C. input sides connected, as shown, to be energized from the secondary windings **135a**, **135b**, **135c** of the transformer T^3, with the variable impedance windings **106a**, **106b**, **106c** connected respectively in series therewith. Across the D. C. output terminals of the rectifier bridges RB^2, RB^3, RB^4 are connected, as shown, the resistors R^{22}, R^{23}, R^{24} respectively, and as will now be clear, the unidirectional potential drops across them very substantially proportionately as the currents called for by the respective interfaces with which they are interrelated by way of the above described variable impedance devices. Conductors **142**, **143**, **144** connect one side of each of these resistors, by conductor **145**, to a fixed contact of the double-throw switch SW, as shown, so that when the switch SW is thrown to the right the resistor R^2 across the current-responsive circuit **107**, **108** is taken out of the earlier above-described circuit in relation with the winding IW^4, and the right-hand ends of resistors R^{22}, R^{23}, R^{24} are connected through the switch SW to conductor **87** of the constant voltage circuit **86**, **87**. Each of the resistors R^{22}, R^{23}, R^{24} is provided with a tap, and the latter are connected, respectively by conductors **125a**, **125b**, **125c** to the respective terminals **122a**, **122b**, **122c**, to which, internally of the preamplifier MA^1, one side of the series-connected windings IW^2, IW^3, IW^4 are connected; the other terminals **121a**, **121b**, **121c** of these windings are connected respectively by conductors **123a**, **123b**, **123c** through the respective rectifiers or valves UV^2, UV^3, UV^4 to the tap of resistor R^7. The tap on resistor R^7 and the taps on resistors R^{22}, R^{23}, R^{24} are so adjusted that the voltage drop across the resistor R^7 equals the voltage drop across the adjusted portion of resistors R^{22}, R^{23}, R^{24} when each interface calls for and receives its safe maximum current, illustratively 30 amperes; the settings of resistors R^{22}, R^{23}, R^{24} may thus be identical.

With this arrangement, that is, with switch SW thrown to the right, compensation for voltage decline in the power amplifier MA^2 may be effected by the devices **CO–106**, rectifier bridge RB^1 and current-responsive voltage drop across resistor R^3, all coacting to vary the energization of windings RW as above described, and thus again maximum stock removal from the work-piece achieved for whatever conditions exist at the respective interfaces and respectively calling for corresponding current flow. However, should any one interface call for current in excess of the safe maximum current, illustratively 30 amperes, thus tending to approach a detrimental or damaging condition or action, the corresponding preamplifier current-responsive winding is brought into action to cut down on the output of the power amplifier MA^2 and prevent the power amplifier from supplying excessive current to that interface; any one of the several interfaces may initiate and effect this protective action and control through its respectively allocated current-responsive winding in the preamplifier MA^1.

For example, were the interface between the conductive element CR^2 and the work W to call for more than 30 amperes, the current-responsive voltage across the selected portion of resistor R^2 exceeds that across the selected portion of the resistor R^7, the resultant voltage difference acting in a direction to cause current flow through the windings IW^2 in the direction permitted by the unidirectional value UV^2. This protective action takes place in a circuit which extends from terminal **121a** of windings IW^2, conductor **123a**, rectifier UV^2, tap on resistor R^7, then resistor R^7, conductor **87**, switch SW (to the right), conductor **145**, conductor **142**, resistor R^{22}, and by conductor **125a** to the other terminal **122a** of windings IW^2.

For the interface between conductive element CR^3 and the work W, the circuit for the current-limiting action extends from terminal **121b** of preamplifier windings IW^3, conductor **123b**, rectifier valve UV^3, resistor tap, resistor R^7, conductor **87**, blade of switch SW (to the right), conductor **145**, conductor **143**, resistor R^{23}, and then by conductor **125b** to the other terminal **122b** of preamplifier **122b** of preamplifier series windings IW^3.

For the interface between conductive member CR^4 and work W, the corresponding circuit extends from terminal **121c** of preamplifier windings IW^4, conductor **123c**, rectifier valve UV^4, resistor tap, resistor R^7, conductor **87**, blade of switch SW (to the right), conductor **145**, conductor **144**, resistor R^{24}, and then by conductor **125c** to the other terminal **122c** of the windings IW^4.

In this manner the selected safe maximum current value cannot be exceeded at any of the several work-wheel interfaces, any one of which can thus bring into effective action its corresponding protective circuit and control winding effective upon the preamplifier MA^1, and accordingly, any of the windings IW^2, IW^3, IW^4 of the latter can be made effective to cause the preamplifier sufficiently to energize the power amplifier control winding CW preponderantly or in opposition to the windings BW and RW to limit or reduce the total current output of the power amplifier and thus protect the work-wheel interface that called for protection; such protective action continues for so long as damage-inviting conditions continue to exist at the particular work-wheel interface, and when such conditions are changed or removed operations can continue as before with compensation for voltage decline effected through the power amplifier winding RW and voltage regulation through the preamplifier winding VW, and their respective energizing circuits as above described.

Where, in stock removal by electrolytic decomposition, the wheel comprises several conductive elements, such as the elements CR^2, CR^3, CR^4 of Figures 4, 6 and 8, the current-responsive magnetically-coupled variable impedance devices associated with the branch circuits **104a**, **104b**, **104c** that lead to the respective conductive wheel elements coact to achieve a number of practical advantages in that, though the current flowing through these branch circuits may differ substantially from each other, these devices, while current-responsive, are ineffectual to cause perceptible or material voltage drops in the branch circuits and accordingly, the potentials of the conductive elements CR^2, CR^3, CR^4 are dependably maintained the same and accordingly no material potential differences exist between the conductive wheel elements, which are usually closely spaced together (see Figures 4 and 6), and material electrical interaction between or among them does not take place. Where any substantial potential difference exists between or among them, in an electrolytic system, one could cause electrolytic decomposition or

"etching" to take place at another, the more positive conductive element feeding current through the electrolyte on the wheel surfaces to its more negative neighboring element. However, the devices I employ efficiently prevent such interactions from taking place.

In both Figure 7 and Figure 8, by appropriately setting the tap on resistor R^6 the power amplifier PW is, through the bias windings BW thereof, set or adjusted to provide the selected voltage at its output terminals **74, 75** suitable for the particular stock removal operation at hand; preferably this adjustment is so made for zero energization of the voltage-compensating control windings RW and of the control windings CW; the windings CW in the illustrative operation of the system above described, are energized by the preamplifier MA^1 which, by setting of the tap on resistor R^9, biases the preamplifier so that its output is zero, the amplifier being at or just below cut-off, in its bias. For whatever the particular stock removal operation the tap on transformer secondary **135** and/or the tap at resistor R^3 are correspondingly set, that is, according to the general current load represented by the particular stock removal operation, to energize the power amplifier windings RW in a direction additive to the effect of the bias windings BW so that, with current increases, the voltage at the power amplifier output **74, 75** does not materially drop, thus effecting compensation for voltage decline and coacting to provide output voltage that is more or less constant in value, aided by the action of the voltage-responsive windings VW of the preamplifier and which, when energized, bias the preamplifier above cut-off so that power amplifier windings CW are energized in opposition to the additive effects of windings RW and BW and thus bias the power amplifier downwardly and hold the voltage of its output from materially exceeding the selected or desired value. Should the work-wheel interface or interfaces call for excessive current at any time, windings IW in Figure 7 or any one or more of windings IW^2, IW^3, IW^4 of Figure 8 become energized to bias the preamplifier MA^1 above cut-off and thus achieve energization of power amplifier windings CW to limit current flow to the work-wheel interface or interfaces, in response to call from the latter for more than a safe value of current. In the arrangement of Figure 8 wider flexibility and adaptability is provided in that by selectively positioning the switch SW the several work-wheel interfaces may conjointly effect limitation of total current flow or may individually do so, according to respectively different stock removal operations, of which several comparative illustrations were set forth above. Or, as will now be clear, and according to desire and circumstances, the system of Figure 8 may be operated permanently with the circuit arrangement corresponding to that provided with the switch SW thrown to the left or may be permanently operated with the arrangement provided when the switch SW is thrown to the right.

The system and apparatus provided in this invention will thus be seen to achieve the various objects above noted or indicated, together with many thoroughly practical advantages. The widely varying work-wheel interface conditions effect dependable control of the electrical energy supplied thereto and thus the apparatus and system can readily meet the many and varied requirements met with in many and various types of grinding operations; moreover, where the plant or factory is already equipped with alternating current energy supply, these and many other advantages are attained by dependable and flexible controls by the interface conditions of the conversion of the alternating current energy to direct current energy.

Current and voltage values at the work-wheel interface or interfaces set out above will be understood to be illustrative, for by the various circuit arrangements and adjusting devices, such as adjustable taps on resistors and transformer windings, a wide range of standards of operation at other current or voltage values is achievable according to the particular grinding operation or requirements to be met.

Also, in other respects the system and apparatus provide flexibility; for example, in both Figure 7 and Figure 8 the above-described setting of resistor R^6 may be made so that the bias windings BW bias the power amplifier PW for full-conduction rather than to provide, as in the above illustration, the selected voltage at its output terminals **74, 75**, whereupon regulation of the output voltage proceeds under the action and control of the voltage-compensating control windings RW and of the control windings CW as the latter are in turn controlled by the voltage-responsive windings VW of the pre-amplifier MA^1. Such setting is preferred where the voltage-compensating windings RW are, as is usually the case, relatively not too powerful, acting principally to add only a relatively small positive bias in order appropriately to compensate for voltage drop in response to current increase, and vice versa, and where the voltage-controlled response of the windings CW do not contribute positive bias because of the blocking action of the rectifier UV.

In any case, so far as the operator is concerned, the apparatus may be by him operated and controlled with few and simple panel controls which, in view of all of the foregoing, will be seen to be the two controls for the resistors R^7 and R^8, and in the case of the arrangement of Figure 8, also the switch SW, with, of course, a main on-off switch.

The system and apparatus will thus be seen to be thoroughly practical, dependable and well adapted to achieve dependable self-protection and safety of use or operation throughout widely varying conditions met with in practice.

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 matter hereinabove set forth, or shown in the accompanying drawings, is to be interpreted as illustrative and not in a limiting sense.

I claim:

1. In electrolytic grinding apparatus, in combination a work-support and rotatable wheel means having a plurality of conductive parts insulated from each other whereby a conductive work-piece and the faces of the wheel conductive parts are interrelated for relative movement therebetween, with means for supplying liquid electrolyte to the interfaces between the work-piece and said conductive parts for electrolytic decomposition at the work-piece face, a saturable-core magnetic amplifier having power winding means energized by alternating current and having rectifier means in circuit therewith to provide unidirectional current at its output terminals and having control winding means for affecting the core saturation thereof, a saturable-core control magnetic amplifier having power winding means energized by alternating current and having rectifier means in circuit therewith for energizing said control winding means of said first magnetic amplifier and having control winding means comprising a plurality of individual windings, one for each of said interfaces, for affecting its own core saturation, means connecting the positive side of said output terminals to the work-piece and a plurality of circuits connecting the negative said thereof to said wheel conductive parts to form a plurality of parallel electrolytic decomposition circuits, a plurality of current-responsive means, each comprising a para-magnetic core coupling member having an inductive winding thereon energizable by alternating current, there being one for each of said interfaces thereby forming a group and those of said group having their coupling members inductively coupled to respective conductors of said parallel circuits whereby to respond to the magnetic fluxes of the respective unidirectional interface currents flowing in said parallel circuits and there being another which has its coupling

member inductively coupled to respond to the flux of the unidirectional current flowing in the circuit connecting said output to said workpiece, and means for selectively effecting energization of a plurality of said individual control windings under the control respectively of the current-responsive means of said group or effecting energization of one of said individual control windings under the control of said other current-responsive means.

2. In apparatus as claimed in claim 1 in which said last-mentioned means for selectively effecting energizing of said control winding comprises means for blocking effective energization of the control winding except as energizing current exceeds a selected value.

3. In electrolytic grinding apparatus, in combination, a work-support and rotatable wheel means having a plurality of conductive parts insulated from each other whereby a conductive work-piece and the faces of said wheel conductive parts are interrelated for relative movement therebetween, with means for supplying liquid electrolyte to the interfaces between the work-piece and said conductive parts for electrolytic decomposition at the work-piece face, a saturable-core magnetic amplifier having power winding means energized by alternating current and having rectifier means in circuit therewith to provide unidirectional current at its output terminals and having control winding means for affecting the core saturation thereof, a saturable-core control magnetic amplifier having power winding means energized by alternating current and having rectifier means in circuit therewith for energizing said control winding means of said first magnetic amplifier and having control winding means comprising a plurality of individual windings, one for each of said interfaces, for affecting its own core saturation, means connecting the positive side of said output terminals to the work-piece and a plurality of circuits connecting the negative side thereof to said wheel conductive parts to form a plurality of parallel electrolytic decomposition circuits, means responsive to current flow across said interfaces for affecting said control winding means of said power amplifier in a direction to substantially maintain the voltage across said parallel interfaces against changes caused by changes in current demanded thereby, means responsive to changes in voltage across said parallel interfaces above a selected value for energizing said control winding means of said control amplifier to affect its energy supply to said power amplifier control winding means and thereby prevent substantial upward departures in voltage across said interfaces, whereby, under the resultant substantially constant voltage across all of the latter, the currents across said interfaces may vary relative to one another as respective conditions thereat change, a plurality of current-responsive means, one for each of said interfaces and respectively responsive to the currents across said interfaces, and means for energizing said plurality of individual control windings respectively under the control of said plurality of current-responsive means and each in response to current flow across its associated interface of a value approaching detrimental arcing thereat and thereby affect the energy supply from said control amplifier to said control winding means of said power amplifier to limit current output of the latter below arcing current value at any of said interfaces and maintain substantially the same applied voltage across all of said parallel interface circuits.

4. An apparatus as claimed in claim 3 in which said last-mentioned energizing means comprises a plurality of circuits, one for each of said current-responsive means, adapted to be energized by alternating current and each including an inductive winding, said current-responsive means each comprising a saturable core having one of said inductive windings inductively related thereto to vary the impedance thereof and each core being inductively related to one of said interface parallel circuits and having its magnetization affected by the magnetic flux of the unidirectional current called for by the respective interface.

5. In electrolytic grinding apparatus, in combination, a work support and a conductive rotatable member whereby a conductive work-piece and said member are interrelated for relative movement therebetween, with means for supplying electrolyte to the interface between the work-piece and said member for electrolytic decomposition at the work-piece face, a saturable-core magnetic amplifier having power winding means energized by alternating current and having rectifier means in circuit therewith to provide unidirectional current at its output terminals and having control winding means for affecting the core saturation thereof, a saturable-core control magnetic amplifier having power winding means energized by alternating current and having rectifier means in circuit therewith for energizing said control winding means of said first magnetic amplifier and having control winding means for affecting its own core saturation, means connecting the positive side of said output terminals to the work-piece and the negative side to said conductive member to provide for electrolytic decomposition at the work-piece face, means responsive to interface current changes for affecting said control winding means of said first amplifier in a direction to substantially maintain the voltage across said interface against changes caused by changes in current demanded thereby, means responsive to changes in voltage across the interface above a selected value for energizing said control winding means of said control amplifier to affect its energy supply to said power amplifier control winding means and in direction to prevent substantial upward departures in voltage across said interface, whereby current demanded thereby may vary with interface conditions, current-responsive means responsive to the current across the interface, and means for energizing said control winding means of said control amplifier in response to a selected value of interface current such as a current approaching detrimental arcing value and operating under the control of said last-mentioned current-responsive means and thereby limit current output of said power amplifier by the action of the energy output of said control amplifier upon the control winding means of said power amplifier.

6. An apparatus as claimed in claim 5 in which said last-mentioned energizing means comprises a circuit energized by alternating current and including an inductive winding, said last-mentioned current-responsive means comprising said inductive winding and a saturable core inductively related thereto to vary the impedance thereof, said core being inductively coupled to the circuit of said interface whereby said impedance varies with changes in the magnetic flux of the unidirectional interface current.

7. An apparatus as claimed in claim 6 in which the circuit which includes said inductive winding is connected to the input of a rectifier means of which the unidirectional output has connected to it said control winding means with means interposed therebetween for blocking current flow to said control winding means except above a selected value corresponding to interface current approaching said detrimental arcing value.

8. In apparatus for electrical stock removal from a conductive work-piece, in combination, means for effecting stock removal from a conductive work-piece by ionic current flow from the work-piece face comprising conductive means and means including a work support for interrelating the conductive means and the work-piece for relative movement therebetween during stock removal, means for supplying unidirectional electrical energy to the interface between the work-piece and said conductive means comprising electromagnetic power winding means energized at its input by alternating current and having a direct-current output with its output connected by conductors to said work-piece and said conductive means with means affecting the output energy comprising saturable core means having control winding

means affecting the magnetic saturation of said core means, and means for controlling the output of said energy-supplying means comprising a circuit energized by alternating current and including an inductive winding having a saturable core inductively related to one of said conductors whereby flux proportional to unidirectional interface current affects said core to vary the impedance of said inductive winding and thereby vary the alternating current in said circuit and means for energizing said control winding means with unidirectional current including a rectifier associated with said circuit and having an output that varies substantially proportionally with said impedance.

9. An apparatus as claimed in claim 8 in which said last-mentioned means comprises means for blocking current flow to said control winding means except above a selected value corresponding to interface current approaching a detrimental arcing value.

10. An apparatus as claimed in claim 8 in which said last-mentioned means comprises means providing a selectable reference potential, means associated with said circuit and providing a potential that varies substantially as the current in said circuit is varied by the interface current flux effect upon said inductively related saturable core, and means interrelating said two last-mentioned means and said control winding means with the energization of the latter responding to the difference between said two potentials.

11. In an apparatus for electrical stock removal from a conductive work-piece, in combination, a work-support for the work-piece, a plurality of conductive parts for coaction in electric stock removal from the work-piece face and providing with the latter a plurality of interfaces which are variable as to number and conductivity thereacross as relative movement takes place between the work-piece and said conductive parts, means for supplying electrical energy having conductive for connecting its output in respective parallel circuits to said conductive parts and to the work-piece and having control means for controlling the energy delivered at the output of said source, a plurality of current-responsive means, one for each of said parallel circuits and responsive to the respective interface currents thereof and another for the circuit connecting said output to the work-piece and responsive to the total interface current, and selectively-operable means for effecting control of said control means by the plurality of current-responsive means respectively associated with said parallel circuits or by the current-responsive means associated with said work-piece circuit.

12. In an apparatus for electrical stock removal from a conductive work-piece, in combination, a work-support for the work-piece, a plurality of conductive parts for coaction in electric stock removal from the work-piece face and providing with the latter a plurality of interfaces which are variable as to number and conductivity thereacross as relative movement takes place between the work-piece and said conductive parts, means for supplying electrical energy having conductors for connecting its output in respective parallel circuits to said conductive parts and to the work-piece and having control means adapted to affect the voltage and current of the energy delivered at the output of said source, a plurality of current-responsive means, one for each of said parallel circuits and responsive to the respective interface currents thereof and another for the circuit connecting said output to the work-piece and responsive to the total interface current, means responsive to said last-mentioned current-responsive means for affecting said control means in direction to maintain the voltage across said interfaces substantially constant throughout changes in total interface current, and means for affecting said control means in direction to depress the voltage of said output and operating under the control of any one of said current-responsive means respectively associated with said parallel circuits according as and when interface current in any of the latter exceed a selected safe stock-removal value.

13. An apparatus as claimed in claim 11 in which the current-responsive means respectively associated with said parallel circuits each comprises a variable inductance having a winding and a core therefor, the cores being inductively related to the respective conductors of said parallel circuits and affected by the respective fluxes of the interface currents carried thereby whereby to avoid detrimental differences in potential among said plurality of conductive parts.

14. An apparatus as claimed in claim 12 in which the current-responsive means respectively associated with said parallel circuits each comprises a variable inductance having a winding and a core therefor, the cores being inductively related to the respective conductors of said parallel circuits and affected by the respective fluxes of the interface currents carried thereby whereby to avoid detrimental differences in potential among said plurality of conductive parts.

15. An apparatus as claimed in claim 12 in which said current responsive means associated with said work-piece circuit is provided with means operating under its control to affect said control means in a direction to depress the voltage of said output when interface current exceeds a selected value, and means selectably operable for placing said control means under the control of either said last-mentioned control means or said plurality of current-responsive means respectively associated with said parallel circuits.

16. In an apparatus for electrical stock removal from a conductive work-piece, in combination, a work-support for the work-piece, a plurality of conductive parts for coaction in electric stock removal from the work-piece face and providing with the latter a plurality of interfaces which are variable as to number and conductivity thereacross as relative movement takes place between the work-piece and said conductive parts, means for supplying electrical energy and having conductors for connecting its output in respective parallel circuits to said conductive parts and to the work-piece and having control means adapted to affect the voltage and current of the energy delivered at the output of said source, a plurality of current-responsive means, one for each of said parallel circuits and responsive to the respective interface currents thereof, said current-responsive means each comprising a variable inductance having a winding and a core therefor, the cores being inductively related to the respective conductors of said parallel circuits and affected by the respective fluxes of the interface currents carried thereby whereby to avoid detrimental differences in potential among said plurality of conductive parts, and means for affecting said control means in direction to depress the voltage of said output and operating under the control of said current-responsive means when any interface current exceeds a selected safe stock-removal value.

17. In apparatus for electrical stock removal from a conductive work-piece, in combination, means for effecting stock removal from a conductive work-piece by ionic current flow from the work-piece face comprising conductive means and means including a work-support for interrelating the conductive means and the work-piece for relative movement therebetween during stock removal, and means for supplying unidirectional electrical energy to the interface between the work-piece and said conductive means and having conductors for connecting the positive side and the negative side respectively to the work-piece and to said conductive means and having control means adapted to control current flow to said interface, said control means including a circuit energized by a source of alternating current and having variable impedance means comprising an inductive winding in the circuit with means inductively associating it with the undirectional magnetic flux produced by the unidirectional current in one of said conductors and variably

demanded by said interface as conditions between the work-piece and said conductive means vary, said circuit having therein means including rectifier means for converting alternating current changes in the circuit to a substantially proportionally varying unidirectional potential, and means responsive to change in said unidirectional potential that correspond only to interface current increase above a selected safe stock-removal value for affecting said control means in a direction to limit current flow to said interface.

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