

Module 5

Power Source For Welding

**PART OF THE GCIL
CERTIFICATE PROGRAMS**

GOODERHAM **CENTRE**
FOR INDUSTRIAL LEARNING

5

5

5

Table of Contents

Issue Date: 05/00
Copyright: 1996, 2000

Terms and Definitions	5
Electrical Symbols	7

Section 1: Introduction

What is an Arc?	9
What is Required to Start and Sustain an Arc?	10
Sources of Power for Welding Arcs	10

Section 2: Electrical Principles

Electrical Sources	12
Conduction of Current	12
Resistance	13
Electrical Power	14
Resistors in Series	15
Potentiometer Circuit	16
Rheostat Circuit	17
Parallel Circuits	17
Graphical Circuit Analysis	18
AC Circuit Analysis	19
Inductance	22
Phase Shift	24
Power Factor	26
Capacitance	26
Power Factor Correction	27
Electromagnetic Induction	28
Rotating AC Generator	30
AC Alternator	31
DC Generators	32
Multi-Phase Generators	33
Three-Phase Source Connections	33
Transformers	34
Transformer Taps	35
Solid-State Diodes	36
Rectification of AC	37

Section 3: Characteristics of Welding Arcs

Conduction of Current in Solids and Gases	38
Ionization	39
Electrical Breakdown	40
Conduction of Current in the Arc	40
Polarity and Current Flow	41
Arc V-I Characteristics	42
Process Polarity	43

Section 4: Process Characteristics and Power Requirements

Gas Tungsten Arc Welding	44
Plasma Arc Welding	44
Gas Metal Arc Welding	45
Flux Cored Arc Welding	45
Submerged Arc Welding	45
Shielded Metal Arc Welding	46

Section 5: Arc Welding Equipment Design

Early Power Source Technologies	47
DC Generators	48
Welding Transformers	49
Transformer Rectifier Technology	50
Silicon Controlled Rectifiers (SCR) - Thyristors	51
Silicon Controlled Rectifier Technology	52
Transistor Circuits	54
Transistor Controlled Machines	55
Switching Circuit	55
Inverter Technology	56
Inverter Control Methods	58

Section 6: Power Source Control Systems

Manual versus Automatically Controlled Arcs	59
Power Source Droop	59
Constant Voltage/Constant Current	60
CV versus CC Arc Operation	61
Manual Arc Control	61
Manual Arc Control Inputs	62
Self-Regulation of the Arc	63
CV System Control Inputs	64
Voltage Controlled Wire Feed	64
Voltage Controlled Inputs	65
Synergic Welding Control	66
Open Circuit Voltage	67
Short Circuit Current	67
Reactive Current Control	68
Tap Controlled Reactance	69
Magnetic Circuit Controlled Reactance	70
Magnetic Circuit Controlled Transformer	71
Saturable Reactors	72
Inductive Power Factor	73
Electrical Feedback Control	73
Output or Stabilizing Inductance	74
Multi-Process Power Sources	75
Microprocessor Controls	76

Section 7: Arc Starting Systems

Arc Starter Circuits – HF	77
Arc Starter Circuits – Impulse	78
Starting by Shorting	78
Mechanism of Arc Initiation by Shorting	79

Section 8: Special Process Control Features

Pulsing	81
Pulsed GTAW	82
Pulsed GMAW	82
Synergic Pulse GMAW	82

Section 9: How to Select a Welding Power Supply

Primary Application	83
Required Current Range, DC, AC or AC/DC, Power Source Characteristic	84
Duty Cycle	84
Utility Power Availability	85
Additional Features	86
Weight and Portability	86
Robustness and Reliability	86
Complexity	87
Interface to Mechanized or Robotic Equipment	87
Suppliers, Spare Parts, Service, Ease of Repair, Training	87
Funds Available, Return on Investment, and Electrical Efficiency	87

Section 10: Practical Application

Setting Up a System	88
Grounding	89
Cable Size and Length	89
Calibration and Monitoring	91
Electrical Interference From Arc Welding	92
Troubleshooting	93
Fault Types	94
Systematic Identification of Equipment Problems	95
Faultfinding Guide	96

Section 11: Standards and Safety 97**Guides and Exercises** 99**Test and Answer Sheets** 112

Terms and Definitions

Armature	The alloy iron core carrying the coils of insulated wire to be revolved through the magnetic field.
Capacitance	The property of a circuit or device that permits it to store an electrical charge.
Conduct	To serve as a medium of transmission.
Dielectric	Electrically non-conducting.
Electrically Bonded	To provide a low impedance path obtained by permanently joining all non-current carrying metal parts to assure electrical continuity and having the capacity to conduct safely any current likely to be imposed on it.
Electromotive Force	That which tends to produce a flow of electricity from one point to another.
Electrostatic	A potential charge of electricity at rest, such as a battery or other storage device.
Ferromagnetic	Highly magnetic, as is iron, or an easily magnetized substance.
Inductance	The ability of a circuit or device to produce induction. Where induction is the production of an electric current in a conductor by variation of a magnetic field in its vicinity.
Impedence	The total opposition to an alternating current presented by a circuit. (The algebraic sum of resistance, capacitance and inductance.)
Inertia	A property of matter whereby any physical body persists in its state of rest or of uniform motion until acted upon by some external force.
Ion	An atom or group of atoms that is not electrically neutral but instead carries a positive or negative charge.
Ionized	To convert or become converted completely or partially by ions.
Reactance	The opposition to an alternating current caused by inductance and capacitance.

Gooderham Centre for Industrial Learning

Resistance	The opposition that a conductor offers to the passage of current, resulting from the conversion of energy into heat, light, etc.
Saturation	The point at which the material has become fully magnetized.
Static V-I Curve	In relation to welding power sources; it refers to the output of the machine when the load is constant or non-fluctuating. The graph is created by applying a steady load and measuring the power source output response.

Electrical Symbols

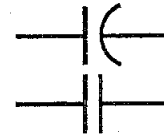
AC voltage source



battery



capacitor



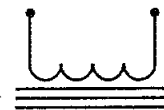
diode



ground(earth)



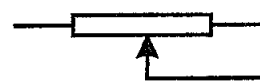
inductor(iron core)



or



potentiometer



or



resistor(fixed)



or



resistor(variable)



rheostat

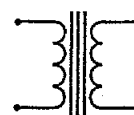


Electrical Symbols Continued

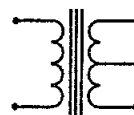
Transfomer(air core)



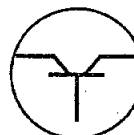
transformer(iron core)



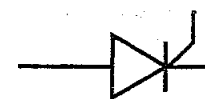
transformer(tapped secondary)



transistor



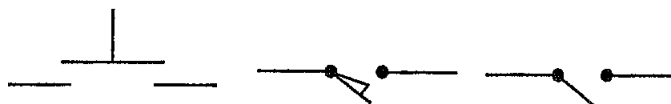
silicon-control-rectifier(SCR)



spark gap



switch(open)



switch(closed)



voltmeter



Power Sources for Arc Welding

Section 1: Introduction

What is an Arc?

An arc is a passage of electric current between two electrodes through a gas, which is in a state that permits it to conduct electricity. Normally gases such as air or argon do not conduct electricity. They have a high resistance to the passage of electrical current and therefore act as insulators. However, in some situations a gas may become **ionized**: the neutral gas atoms are split into gas ions carrying a positive electrical charge, and free electrons carrying a negative charge. The ionized gas is called a "plasma", and now has the capacity to carry current. The most obvious example of an arc in nature is lightning. In a typical lightning strike, electrical potential (the capability of doing work) is gradually built up in the cloud. Very high voltages are developed between the cloud and the ground and eventually the voltage overcomes the high electrical resistance of the air. A lightning strike follows, with a very short discharge of many millions of amps. A welding arc is controlled so that conduction of hundreds of amps can be sustained over a period of time. Arcs have found use in a number of industrial applications such as welding and steel making. High intensity lighting systems in the past commonly used an electric discharge between two carbon electrodes in air to generate an intense source of light.

Electrodes are the components of an electric circuit between which the arc operates. In a typical arc welding application the workpiece will form one electrode, and the other electrode is either a tungsten rod or a filler wire. **Figure 1.1** shows two typical arrangements. When Gas Tungsten Arc Welding (GTAW) with direct current, a negative voltage is applied to the tungsten electrode. Tungsten has a very high melting point and is not consumed as part of the process. When Gas Metal Arc Welding (GMAW) a positive voltage is typically applied to an automatically fed wire electrode which is consumed and forms part of the weld joint.

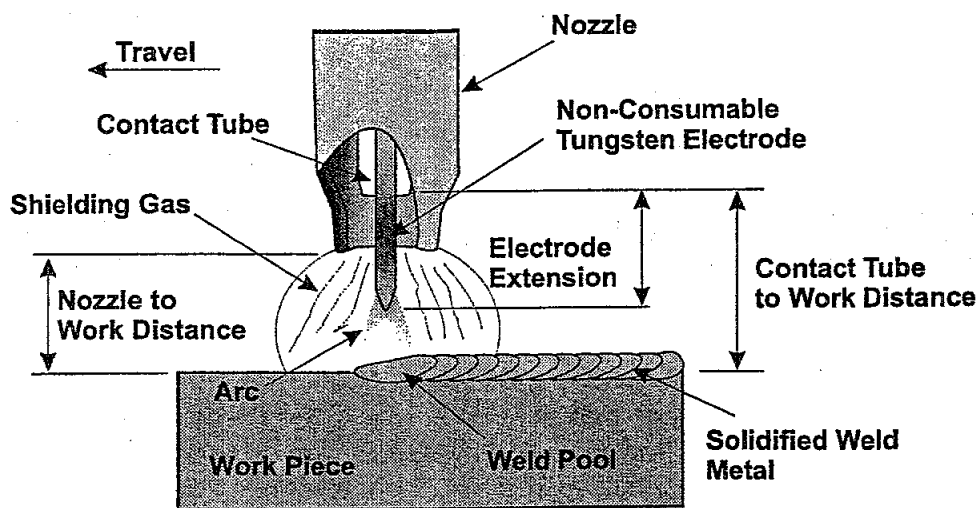


Figure 1.1(a): Gas Tungsten Arc Welding

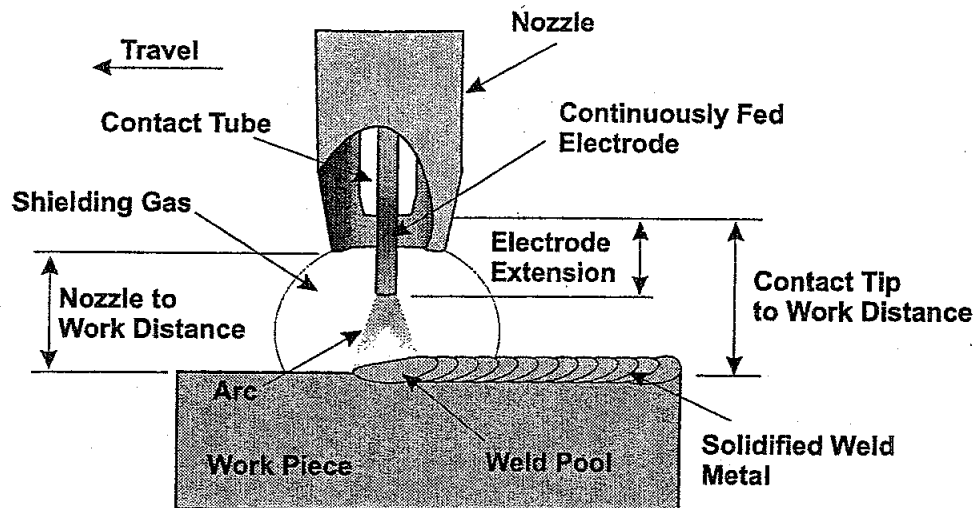


Figure 1.1(b): Gas Metal Arc Welding

For GTAW and GMAW, the arc can be observed as a conical or bell shape region of intense heat and blue-white light. The temperatures in the central column of the arc are extremely high, ranging from 5000°C to $50,000^{\circ}\text{C}$. The majority of the welding current is conducted within the central arc column, and outside this region the temperature falls very rapidly.

What is Required to Start and Sustain an Arc?

One of the simplest ways to start an arc is to touch the electrode to the work piece and then pull it away - known as a touch or scratch start. If the electrode and workpiece are connected to a source of power which is able to supply a suitable voltage and current then an arc can be formed. The arc is sustained by the energy supplied from the power supply. Arcs which form between contacts which are being pulled apart (a switch disconnecting a load), can often cause problems. Electrical circuits are designed to prevent arcs from forming and destroying the switch. Another method of starting an arc is to use a very high voltage to break down the resistance of the gap between the electrode and workpiece (create an ionized column of gas). A high voltage with a low current capacity is used to create a spark. The spark represents the ionized path. The main power source can now supply current through the ionized path. This is one method that GTAW uses to initiate an arc.

Sources of Power for Welding Arcs

One of the earliest power sources for welding arcs were lead acid batteries. Later, specially designed motor generators were used to deliver power in a form suitable for welding, and eventually utility supplied AC power was used with transformers and transformer-rectifiers. In Module 4 you learn that each welding process and consumable combination has a particular requirement from the power supply. The source of power must be designed in such a way that the requirements of the process are matched by its output. Designs of welding power supplies have become increasingly sophisticated. Modern power supplies generally use electronic controls to match the power supply to the requirements of the

process. The advantage of electronically controlled power sources is the ability to meet the needs of many different processes from one machine. Transformer-based machines generally operate from utility supplied power. In field work a gas or diesel driven generator may be used to provide electrical power for welding. In the next section, basic electrical concepts important in arc welding power supplies will be reviewed before moving on to consider the detailed requirements of each arc welding process.

Section 2: Electrical Principles

An understanding of the operation of the welding arc and welding machines requires a review of the fundamentals of electricity, electrical power, and electro-magnetic effects. The purpose of this section is to explain these effects, and describe how they are put to use in practical circuits as used in welding equipment.

Electrical Sources

The most fundamental part of an electrical system is the source of electrical potential, or voltage. **The voltage in an electrical system is equivalent to the force in a mechanical system or the pressure in a hydraulic system.** The potential or voltage is sometimes referred to as the "electromotive force" or "EMF". It is the voltage applied across an electrically conductive "circuit" which produces current flow (flow of electrical charge) through the circuit. The flow of current produces the useful effects in the circuit; the generation of heat, light, or motion.

Electrical potentials or voltages are measured in "volts". The most readily known sources of voltage are batteries. Batteries create a voltage by chemical processes. The voltage is maintained across the terminals of the battery until the electrochemical reaction is used up. The battery must then be replaced or renewed (recharged).

Voltage also can be produced by a process known as **electrical induction**. If a conductor is moved through a magnetic field, a voltage will be generated in the conductor. A voltage can also be induced by moving the conductor through the magnetic field. This is the essential difference between an alternator and a generator. Electrical induction can provide large amounts of electricity on a continuous basis at a wide range of voltage levels. Most large scale sources of electricity use electrical induction.

Conduction of Current

When a conductive circuit made up of wires and electrical components is connected to the output of a voltage source, current will flow from one side of the voltage source, through the circuit, and back to the opposite side of the source. This produces the useful results from an electric circuit. The copper wire generally used in an electrical circuit is a good *conductor* (i.e., it provides low resistance to the passage of current). The convention normally used in engineering is that the current flows from the positive terminal of the source through the circuit to the negative terminal (this is called "conventional current"). In most engineering situations, the convention of current flowing from positive to negative helps in analyzing circuits and making calculations. However, since electrons have a negative charge they flow in the opposite direction. Electrons travel from the negative terminal through the circuit to the positive terminal. **When considering the physical effects caused by arcs, the situation is analyzed in terms of electron flow rather than conventional current.** This is frequently a source of confusion when studying welding processes.

Resistance

The primary characteristic of an electrically conducting circuit attached to a source of voltage is its *resistance* to the flow of current (**Figure 2.1**). The resistance of a circuit is denoted by the symbol, '**R**', and has the units of '**ohms**'. *Ohm's law* states that the current '**I**' which will flow through a circuit with a resistance, **R**, when a voltage, **V**, is applied across it is calculated by:

$$I = V/R$$

where: **I** is current in amperes
R is resistance in Ohms
V is voltage in volts

Ohm's Law is more commonly written:

$$V = IR$$

If the voltage and current flowing through a circuit is known, then the resistance of the circuit can be found by arranging the equation as:

$$R = \frac{V}{I}$$

Ohm's Law is true for metallic conductors. It essentially states that the current flowing in the circuit is directly proportional to voltage. Ohm's law does not apply to some materials such as semiconductors and transistors. Most importantly, **Ohm's Law does not apply to a welding arc**. The current in the arc is not proportional to the voltage across the arc. The arc still has a resistance $R = V/I$, but the resistance is not constant, and depends upon the applied voltage and current, passing through a given media.

The resistance, **R**, of a wire is proportional to its length, "**l**", and inversely proportional to cross sectional area '**A**'. Larger diameter wires have more surface area and thus less resistance. The following formula applies:

$$R = rl/A$$

where: **A** is cross sectional area in square meters
l is length in meters
r is resistivity in Ohm meters

The factor '**r**' is a constant for a metal at a given temperature; called the '**resistivity**' of the material, in units of ohm-m. (Ohms x meters). Metals and their alloys have different values of resistivity. Copper has low resistivity and is therefore a good conductor, titanium has high resistivity and is therefore a poor conductor. Copper is widely used for connections, and conductors where low resistance is required. Welding cables are a good example. Aluminum has higher resistivity than copper but because it also has lower density (lower weight for a given cable size) it has lower resistance per unit

weight than copper. Aluminum has advantages where the weight of the conductor is an issue. For example; electrical utilities use aluminum cables in long, large transmission lines because of its much lighter weight and lower cost.

The resistivity of some common metals at 20°C (68°F) are as follows:

•	Copper	1.7×10^{-8} ohm-m
•	Aluminum	2.7×10^{-8} ohm-m
•	Tungsten	5.6×10^{-8} ohm-m
•	Iron	9.7×10^{-8} ohm-m
•	Titanium	43×10^{-8} ohm-m

Electrical Power

Electrical power is measured in "watts". Power is measured as a combination of the pressure (volts) and the flow rate of current (amperes). If a source supplies a voltage, V , at a current, I , into a circuit, then the electrical power, ' P ', delivered to the circuit in *watts* (joules/second) can be calculated by:

$$P = VI$$

where: P is power in watts

and by using Ohm's Law, another useful formula for power can be derived as:

$$P = I^2 R \text{ or } \frac{V^2}{R}$$

Electrical power is transformed into heat, light, or motion depending upon the device the current is flowing through. In devices such as electric heaters and hair dryers, the electrical energy is transformed into heat (thermal energy). In a light bulb, the filament becomes very hot and some of the energy is transformed into visible light. In a welding arc, energy is transformed mostly into heat, and some light.

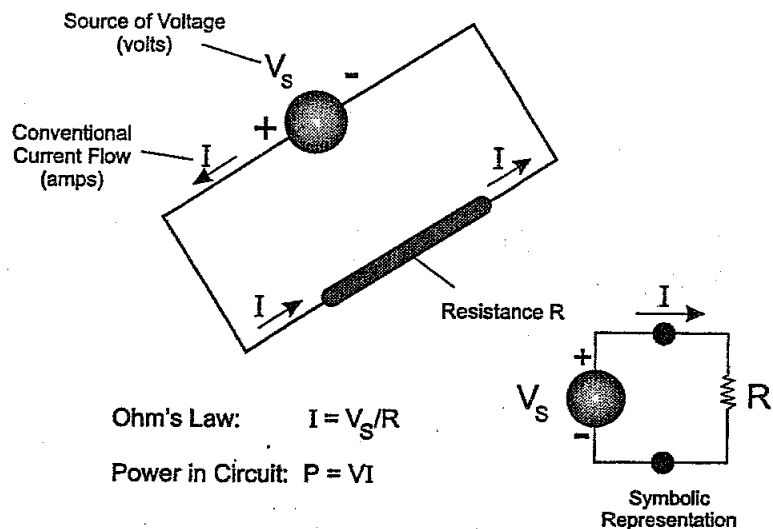


Figure 2.1: Voltage, Resistance, and Current in Electrical Circuits

The analysis of electrical circuits involves applying concepts of conservation of energy and charge. The conservation of energy law states that "...the total energy of an isolated system remains constant regardless of changes within the system." Energy is not created or destroyed, it simply changes from one form to another. For example, the chemical energy stored in a battery is converted into electrical energy which is delivered to the lightbulb of a flashlight where it is converted into light and heat.

Energy delivered to a circuit by the source must be dissipated in the circuit. Current flow in the circuit must always equal that being delivered by the source. This results in two laws:

- **Kirchoff's voltage law** states that around a circuit, (starting at one point and returning to that point) voltages must add up to zero.
- **Kirchoff's current law** states that current flow into any point in the circuit must be balanced by current flow out.

These two laws enable the creation of formulas for determining the resistance in a complex circuit.

Resistors in Series

A series circuit is a circuit with only a single path for current flow. The current must be the same at all points in the circuit and the current delivered by the source must equal that which passes through the resistance. A resistor or resistive device causes a voltage drop as the current passes through. A pure resistor converts energy into heat. If two resistors are in the series circuit, the current must be the same through each resistor. The voltage drop which occurs at each resistor will depend upon the value of the resistance. The sum of the voltage drops across the two must be equal to that from the source. The following formulas are illustrated in **Figure 2.2**:

$$V_1 = IR_1 \text{ and } V_2 = IR_2$$

$$V_S = V_1 + V_2$$

Hence:

$$V_S = IR_1 + IR_2$$

$$V_S = IR_e$$

where: R_e is the total or equivalent resistance of the circuit
 V_S is the total voltage for the circuit.

therefore the total resistance can be written as:

$$R_e = R_1 + R_2$$

Figure 2.2 describes the effect of multiple resistors in a series circuit. Two resistors in a series circuit can be considered to have an "equivalent" resistance. This will be equal to the sum of the two resistances, as far as the power source is concerned. It is often convenient to consider two resistors in series to be represented as a single resistor with an equivalent resistance when making calculations. The voltage drop across each resistor will of course be a function of the value of the resistor. The schematic below illustrates resistors in series;

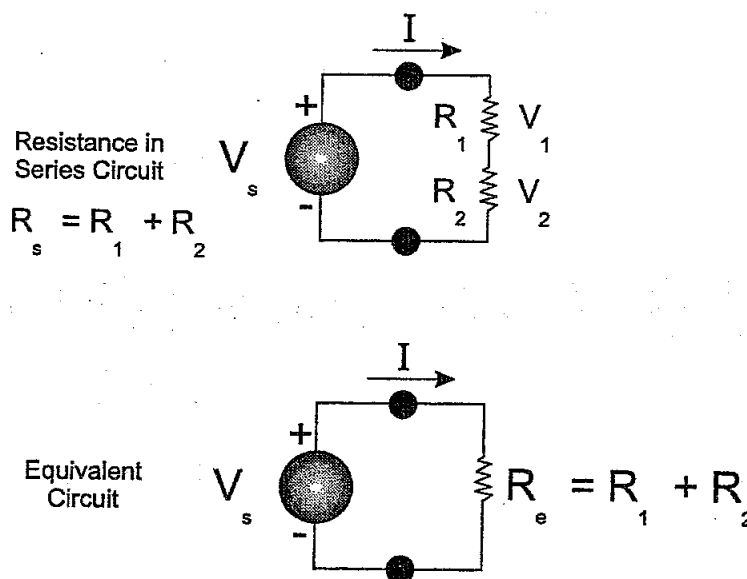


Figure 2.2: Resistors in Series

Potentiometer Circuit

A circuit of two series resistors is often useful as a "voltage-divider" circuit since the voltage across the second resistor is a fraction of the total voltage, as shown in **Figure 2.2**. A potentiometer circuit uses a single resistor with a sliding contact in the middle for a third connection, in essence dividing the resistor into two resistors (**Figure 2.3**). Position of the sliding contact determines the ratio of resistances and, the "output voltage" of the circuit. Variable resistors are often called *potentiometers* or *pots* because they vary the voltage or potential. The potentiometer provides a simple way of generating a variable voltage from a fixed voltage source. Such circuits are often used to provide a varying voltage signal to electrical equipment, the slider position being set by a knob on the control panel of the equipment. See **Figure 2.3**.

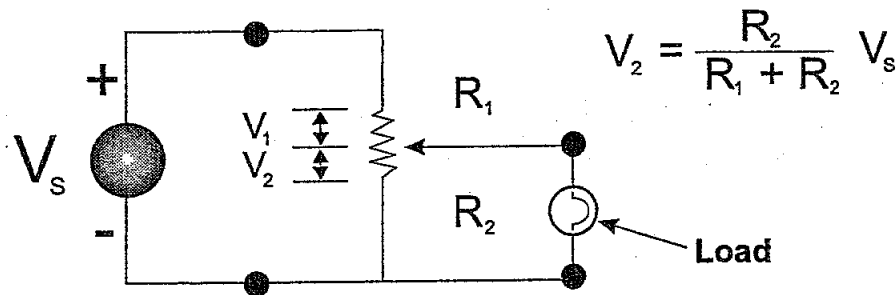


Figure 2.3: Potentiometer Circuit

Rheostat Circuit

Another important series circuit is to place a variable resistance in "series" with an electrical load. This provides a way to control the power fed to a device. In this case, only one end of the variable resistor and the sliding connection are used. The current in the circuit is controlled by changing the total resistance in the circuit. When used in this manner the variable resistor is called a "rheostat" (Figure 2.4). The disadvantage of such a circuit is that a considerable amount of power is lost in the rheostat as heat. Rheostats were commonly used in early electrical circuits for the control of electrical power.

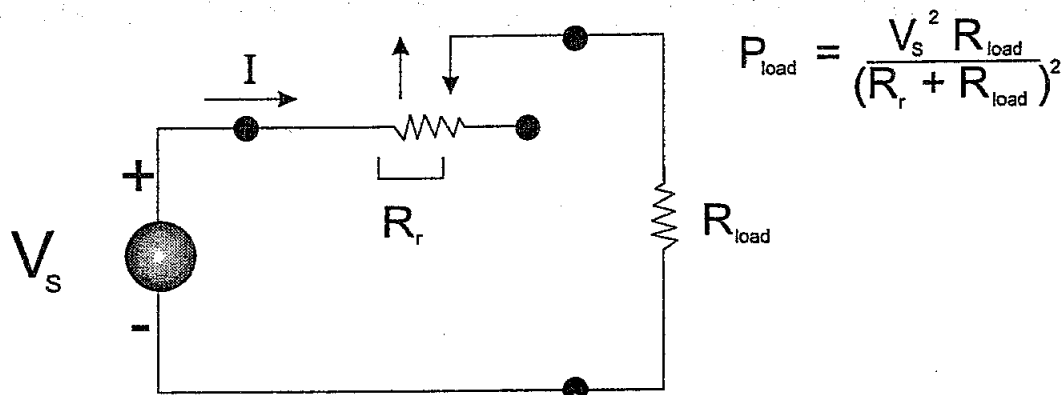


Figure 2.4: Rheostat Circuit

Parallel Circuits

Circuits constructed to allow multiple current paths or branches are called "parallel circuits". The simplest circuit consists of two resistors "in parallel" shown in Figure 2.5. In this case, the voltage must be the same across each resistor since they are connected in common to the same voltage source (Figure 2.5). Current through each resistor depends upon its value of resistance. The currents must sum at the common points - the total current flowing must equal the sum of the currents passing through the two resistors. The equations may be written:

$$I_{total} = I_1 + I_2$$

$$V_S / R_e = V_S / R_1 + V_S / R_2$$

The equivalent or total resistance R_e is given by:

$$1/R_e = 1/R_1 + 1/R_2 \quad \text{or} \quad R_e = \frac{R_1 R_2}{R_1 + R_2}$$

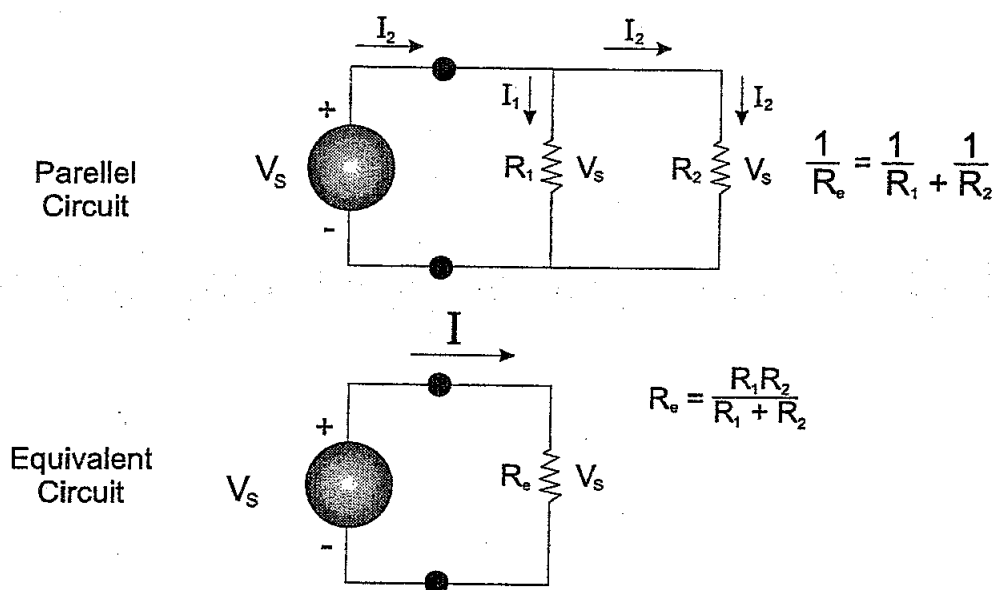


Figure 2.5: Resistors in Parallel

Graphical Circuit Analysis

It is often useful to analyze circuits by graphical methods, rather than with equations. This involves the determination of the so-called Volt-Ampere, or V-I, characteristics of electrical elements in a circuit. Welding power sources are loosely defined by their Volt-Ampere output curves. A **constant voltage** power source will have an output curve which is nearly horizontal. A **constant current** power source will have an output curve which is drooping and nearly vertical over most of the useable range.

In **Figure 2.6** a constant voltage power source is graphed as supplying 20 volts whatever the current in the circuit. This is plotted as a horizontal line on the graph. The load has a resistance value of 0.1 ohms. This is graphed as a line with slope equaling 0.1, since $R = V/I = 0.1$. The intersection of these two lines gives the *operating point*, in this case a current of 200 amps at 20 volts. This simple result could obviously have been found by applying Ohm's law. **But welding arcs do not obey Ohm's law.** Welding power sources often are not true constant voltage (or constant current). Graphical analysis will be seen to be very useful in understanding arc welding processes.

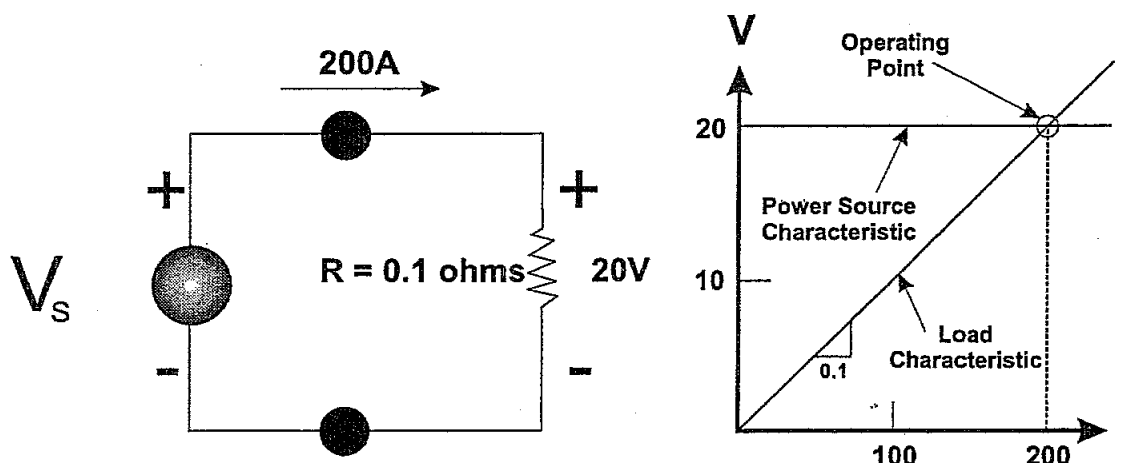


Figure 2.6. Graphical Circuit Analysis

Volt/amp characteristics can be measured experimentally, and then graphed for the purpose of studying and understanding circuit operation. An electrical source characteristic (e.g., power source characteristic) is found by setting the output of the source and then varying the load. This information is then plotted on a graph to show how the power source voltage and current output vary with the changing load. **In arc welding, the arc is a load which varies continuously.** In manual welding especially, changing arc length causes large changes in the 'arc load' on the power source. The power source must then respond to the changing arc load in order to produce smooth welding process operation. The appropriate change in power source output is dependant upon the welding procedure.

The characteristic of an electrical load circuit is found by connecting it to a variable source and plotting how the current, flowing to the load, varies with voltage from the source.

AC Circuit Analysis

A DC voltage source such as a battery produces currents and voltages throughout the circuit which are constant and referred to as *direct current*, or *DC*. Utilities do not supply power as direct current because it is more difficult to raise or lower DC voltage than AC voltage. Generation at electric power plants produces alternating current, or *AC*, where the current varies like a sine wave (**Figure 2.7**). The frequency in Canada and the USA is 60 cycles per second or 60 Hertz (1 Hz = 1 cycle per second). A sinusoidal AC voltage source produces currents, and voltages which vary in a sinusoidal

manner, throughout the circuit. It is useful to note that AC may take on other waveforms such as square waves depending upon the type of source and the desired character of its output. Circuit analysis is essentially the same as that for direct current circuits. The exception is that each voltage and current in the circuit has an *amplitude*, which varies in a sinusoidal fashion at the frequency of the AC voltage source.

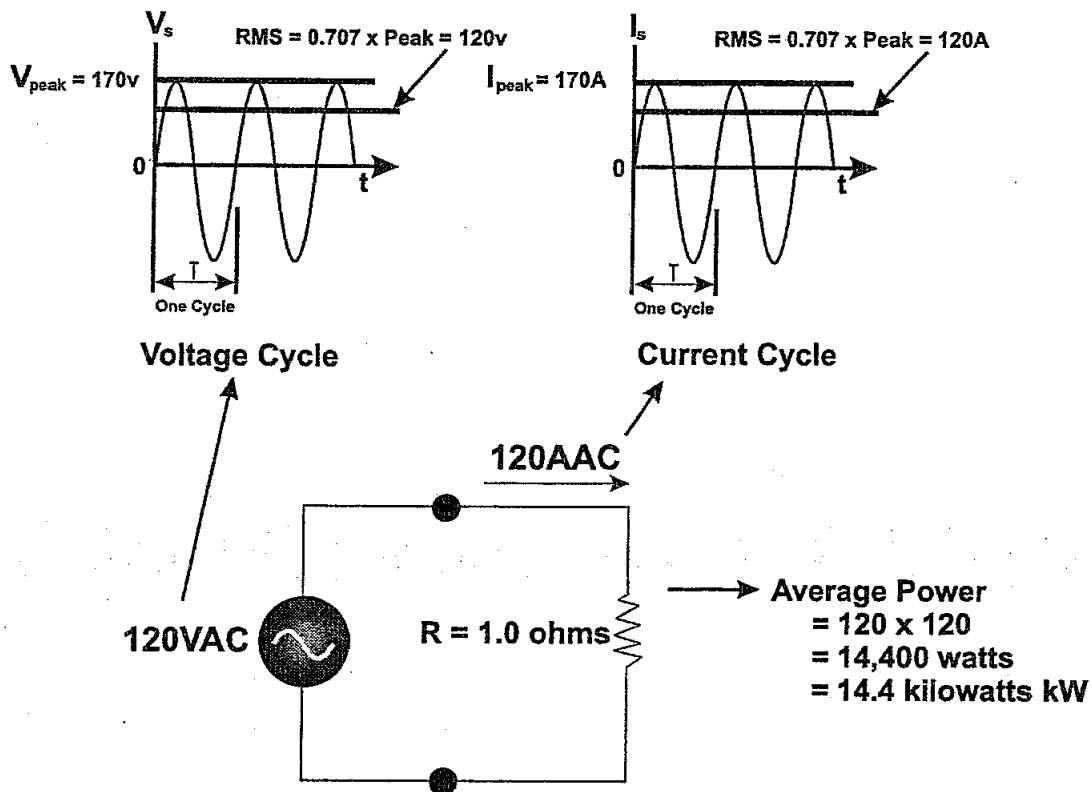


Figure 2.7. AC Circuit Analysis

In an AC circuit, current is positive as often as it is negative. This means that the average current is zero. A DC voltage and current meter measures average voltage and current and therefore cannot be used to measure alternating current. The meter would read "zero" when connected to an AC circuit. However, power is dissipated in AC circuits and is independent of current direction.

It can be shown that if the square root of the average of the square of current and voltage at any time is used for calculation (called the *root mean square*, or *RMS*), then the same formula for power can be used. Hence, for a sinusoidal AC circuit, the power P is given by:

$$P = V_{rms} I_{rms}$$

AC voltage and current meters are designed to measure RMS values. It is the RMS value of current or voltage which is measured and used in AC circuit calculations. Thus, if 120 VAC (RMS) is applied to a 1.0 ohm resistor then 120 AAC (RMS) flows through the resistor. The actual power dissipated in the resistor will be $120\text{VAC} \times 120\text{AAC} = 14,400$ watts. The power dissipation will be exactly the same as if 120 VDC was applied to the resistor.

The peak value of AC voltage is larger than the RMS value. For example, the peak voltage of a standard line voltage of 120VAC is given by:

$$V_{\text{peak}} = \sqrt{2} V_{\text{rms}} = 1.414 \times 120 \text{ volts} = 170 \text{ volts}$$

The actual voltage at a particular point in time can be calculated from the equation for a sine wave. It should be noted that the factor applies only to sinusoidal AC. Other AC waveforms, such as square-wave, have different factors that must be determined and applied.

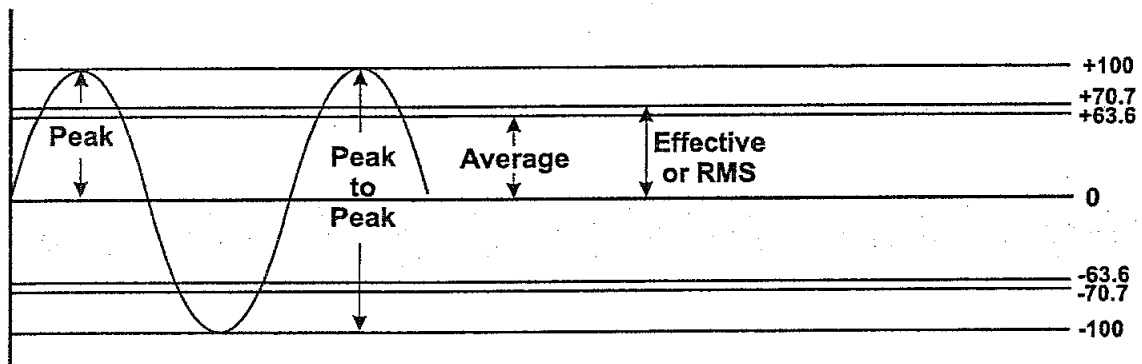


Figure 2.8: Relationships of Various AC Values

The use of RMS amplitudes for AC circuits allows them to be analyzed in an equivalent manner to DC circuits. As a result, AC circuits can often be considered without reference to the sinusoidal nature of the waveform. This greatly simplifies AC circuits. Of course, there are times when the sinusoidal nature must be included for a complete and accurate picture of circuit behavior. The following table can be used for the conversion of various AC values.

Table 2.1: Conversion of AC Sine Wave Values

To Change ↓ To →	Peak	Peak - Peak	Effective RMS	Average
Peak		Multiply Peak by 2	Multiply Peak By 0.707	Multiply Peak By 0.636
Peak - Peak	Multiply Peak - Peak by 0.5		Multiply Peak - Peak by 0.353	Multiply Peak - Peak By 0.318
Effective RMS (Electro-Dynamometer)	Multiply Effective By 1.41	Multiply Effective By 2.82		Multiply Effective By 0.91
Average	Multiply Average By 1.57	Multiply Average By 3.14	Multiply Average By 1.11	

A Triplet Type Meter Will Read:

- 1) RMS on AC**
- 2) Average when reading rectified DC**

Inductance

Inductance is a property of a circuit just as resistance. Any circuit which is capable of producing a magnetic flux has inductance. Any change in the current flowing in circuit causes a change in the magnetic flux. The changing magnetic flux will induce a voltage (emf) and this voltage will oppose the change that produces it. The effect is called a "counter emf".

A coil of wire reacts differently when an AC current is passed through it than when a DC current is imposed. In a DC circuit the inductive effect is realized only when the current is changing (eg. when a switch is turned on or off). Under steady current flow conditions (DC) the coil acts as a pure resistance and has the ability to store energy. In an AC circuit current is changing continually and therefore inductive effects are created (**Figure 2.9**).

When a changing current passes through a coil, a magnetic field is created in the coil. The strength of the magnetic field (flux) changes with the amount of current flow and the speed at which the current flow is changing. The magnetic field induces an "emf" (voltage is often referred to as electro-motive force or emf). The emf induced in the coil will oppose changes in the strength of the magnetic field or "flux". The overall effect is that the coil acts to impede the flow of current in an AC circuit. It will be seen later that inductors (coils) can be used to control the flow of current in a circuit.

If we make an analogy to a mechanical system; the coil in series in an AC circuit acts like a flywheel. A "flywheel" in a mechanical system is used to stabilize speed by the inertia of a spinning mass.

Inertial forces limit the rate that a mass may be accelerated or decelerated by a force in a mechanical system. **The inductance of the coil limits the rate that current may increase or decrease in a circuit by creating an opposing voltage or emf.** This opposing voltage is often referred to as "back emf". In welding power sources this is used to smooth out ripples in the power flow.

The induced emf "E" around a coil is proportional to the rate at which current is changing (AC frequency):

$$E = -L \left(\frac{\Delta I}{\Delta t} \right)$$

Where: E is induced or back EMF in volts

$\Delta I / \Delta t$ is rate of change of current with time, in amperes per second

L is inductance

L is a constant of proportionality for a coil that is called the "inductance". The inductance depends on the numbers of turns of wire and other geometric characteristics. The inductance can be greatly increased by placing iron inside the coil, since iron increases the strength of the magnetic field. Inductance acts rather like a resistance in a DC circuit, and impedes the flow of current. Since the effect of inductance depends on the rate of change of current, therefore the frequency of the AC supply will have direct effect; the higher the frequency, the greater the effect of inductance in a circuit. Because of this, high frequency inverter power supplies are much smaller than line frequency power supplies. Inverter based welding power sources will be discussed later.

Inductance is most commonly encountered in AC circuits where coils called "inductors" are used. The inductance may be purposely added for its unique circuit effect, or it may be associated with the coil in a motor, transformer, solenoid or the like. In any case, it is represented by the inductor symbol in the circuit (**Figure 2.9**). Real circuits always contain some inductance. Even a straight piece of wire creates a small inductive effect.

Purely resistive circuits can be analyzed by following ohms law. Circuits with inductors (and capacitors) are analyzed by different means. Such circuits are said to have *reactive* components, or to be *reactive* circuits. **The effect of inductance (and capacitance) is said to add reactance to the circuit, in addition to the resistance associated with resistors in the circuit.** The effect of reactance in a circuit is expressed by a generalized concept of resistance, called "*impedance*". Impedance combines the effects of inductive and capacitive reactance with the resistance of the circuit. Impedance is the total opposition to current flow in the circuit. Inductance caused by a coil impedes the flow of current in an AC circuit. The amount of impedance an inductor creates is calculated by:

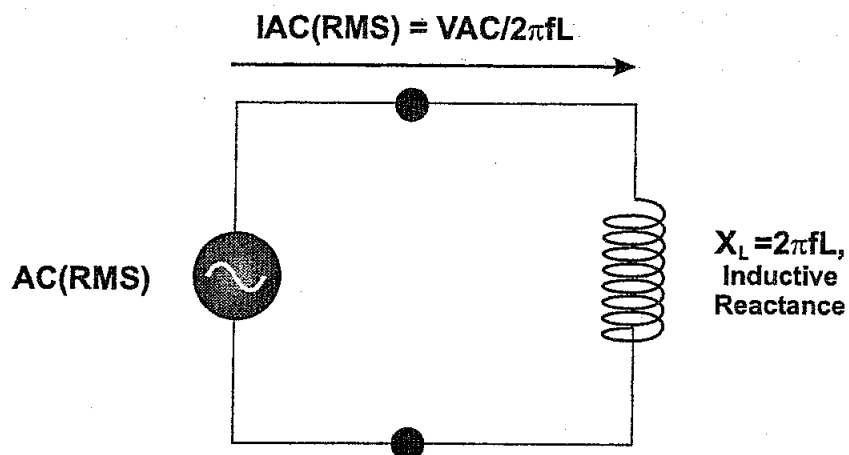
$$X_L = 2\pi fL \text{ ohms, where } f \text{ is the AC frequency in Hertz (cycles per second).}$$

For a pure inductor (a device with no resistance) an equation can be written which is equivalent to Ohms Law:

$$V = IX_L$$

where: $X_L = 2\pi fL$ is called the *impedance* of the inductor.

Inductance has no effect in a DC circuit, and behaves essentially as a short between the two points of circuit connection (neglecting the resistance of the wire coils of the inductor).



f = frequency of AC in cycles per second (Hz)

Figure 2.9: Inductance in an AC Circuit

Phase Shift

When an AC source is connected to a pure resistance, the current increases and decreases in step with the voltage. When the voltage is at a peak, the current is at a peak. When the voltage is zero, the current is zero. Current and voltage rising and falling together are said to be "*in-phase*". Most devices are not pure resistors.

When a pure inductor (coil) is connected to an AC circuit the voltage and current are forced out of phase. The change of current in the circuit produces a "*back emf*" - a voltage which opposes the source voltage. In **Figure 2.10**, the current and voltage are *out-of-phase*. The current reaches its peaks and troughs one quarter cycle (90 deg.) after the voltage does. It is said that *the current lags the voltage by 90 degrees or one quarter cycle*.

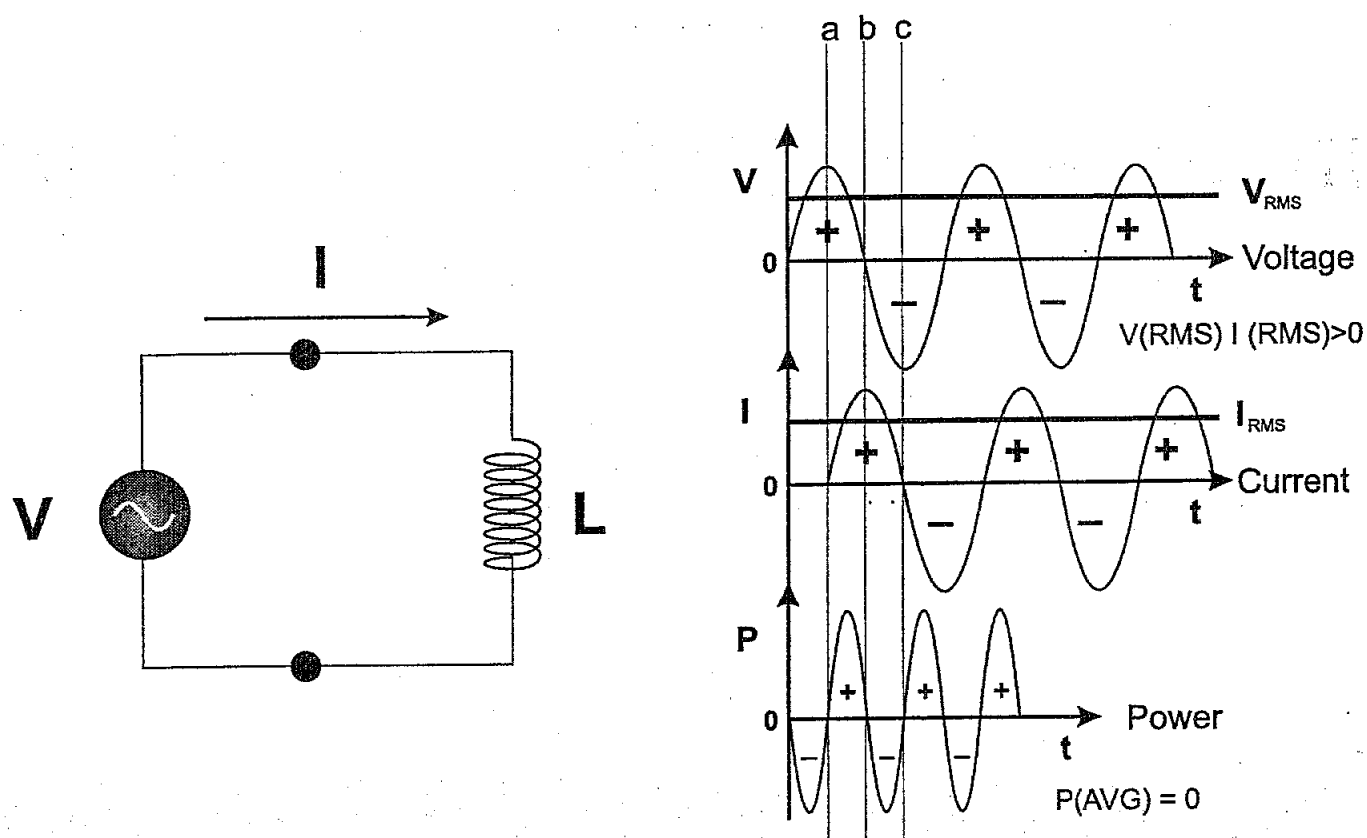


Figure 2.10: Phase Shift

It may be useful here to consider the operation of a hydraulic system. In order to create useful hydraulic power, both sufficient pressure and sufficient volume (flow rate) are needed simultaneously. Pressure and flow rate are needed to do work. Consider a high pressure pump without a reservoir of fluid or a reservoir without a pump to create pressure. In each case no flow occurs and no work is done. Voltage or electro-motive force can often be thought of as the pressure which causes current to flow. Current represents the volume of flow which is passing through the system.

In **Figure 2.10** we see that the rise and fall of voltage and current do not occur together. If we look at the graphs for voltage and current, when voltage is maximum, current is zero. At another moment in time, when current is maximum voltage is zero. In both cases the actual power flow is then also zero.

In electrical terms; current and voltage are said to be *90 deg.* out-of-phase. It can be seen by multiplying the instantaneous value of current and voltage (**Figure 2.10**) that the average power is zero. The inductor effectively stores energy in one quarter cycle, and releases it back to the source in the next quarter cycle.

Using an AC meter we could measure the average voltage and current and calculate an apparent power, but because of the phase shift of 90° the actual average power is zero. This is proven by the lack of any temperature rise in the inductor, as would occur in an equivalent resistance (some small heating would occur in a real inductor due to resistance in the coils of the inductor). An AC volt/amp meter does not measure or account for phase shift.

Power Factor

Power in a DC circuit is equal to current times voltage. Power in an AC circuit is equal to the instantaneous value of current times voltage. When an alternating current and voltage are in phase the power flow is equal to effective current times effective voltage ($0.707 \times \text{Peak}$). **The ratio of the actual electrical power delivered to an AC circuit, to the apparent power is called the "power factor" of the circuit.** In a purely resistive circuit the actual power is equal to the apparent power, and the power factor is one. In real circuits some reactance will be present which shifts the current/voltage peaks out of phase and power factor is no longer one. In a purely inductive circuit the actual power dissipated in the inductor is zero, and hence, the power factor is zero. A circuit with both resistance and inductance will have a power factor between zero and one. Actual electrical power is measured in watts or kilowatts (kW), while apparent power is usually stated in volt-amperes, or kilovolt-amperes (kVA). Actual power in watts is found by multiplying the value of voltamperes by the power factor of the circuit. The value of power factor depends upon how much amperage and voltage are out of phase.

Inductance is most often present in electrical equipment with windings which create inductance, even if not intended. Motors and transformers are primary examples. Most stationary welding machines are transformer based.

From the perspective of the electrical power system, low power factor is bad. It is bad because high current is delivered but useable power is small. The amperage drawn by the load burdens the capacity of the electrical system regardless of the power factor involved. Ten amperes RMS to a zero power factor load will trip a 10 ampere breaker just as readily as will 10 amperes to a purely resistive (power factor one) load. When supplying a low power factor load, the electrical system is circulating power, rather than doing work. The power supplier prefers to deliver to high power factor loads. This maximizes the utility's electrical capacity to deliver power. Power companies often have a rate system that penalizes low power factor loads. This motivates the user to either provide *correction* of power factor, or to minimize inductance in electrical equipment designs. When purchasing a welding machines it is common to consider the "power factor correction" option. Power factor considerations are especially important when a facility has many welding stations.

Capacitance

A *capacitor* is a circuit component which can be considered to be complimentary to inductance. *Capacitance* involves electrostatic phenomena, related to charge build-up or charging of conducting elements in the circuit. Capacitors involve two conductive plates or sheets brought into close proximity, separated by a non-conductive medium called a "*dielectric medium*" (**Figure 2.11**). In a DC circuit, a capacitor acts like an open connection (infinite resistance), but in an AC circuit a capacitor conducts current in proportion to the rate of change of voltage across the plate elements.

A relationship between the applied voltage in a capacitor can be written just as for an inductance:

$$V = IX_C$$

Here the capacitive reactance X_C is given by:

$$X_C = 1/2fC$$

where: C is the capacitance in Farads.

Note that for DC, $f = 0$, and hence X_C is infinite, and the current will be zero.

Capacitance in an AC circuit produces a similar (but actually complimentary) effect to inductance. In a purely capacitive AC circuit, the current *leads* the voltage by 90 deg. (one fourth cycle), rather than lagging as in the inductive circuit. It would again be found that the average power delivered to the capacitor over one cycle of the AC is zero, thus the circuit would have a power factor of zero. The absence of any power delivery is manifested by a lack of any rise in temperature of the capacitor.

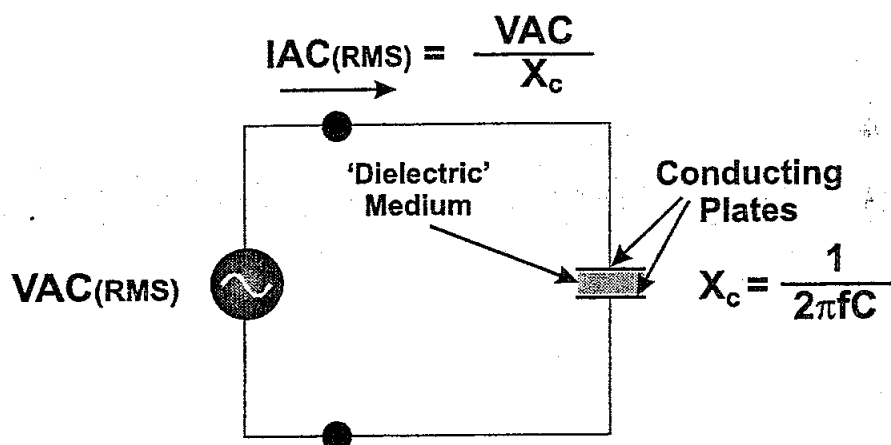
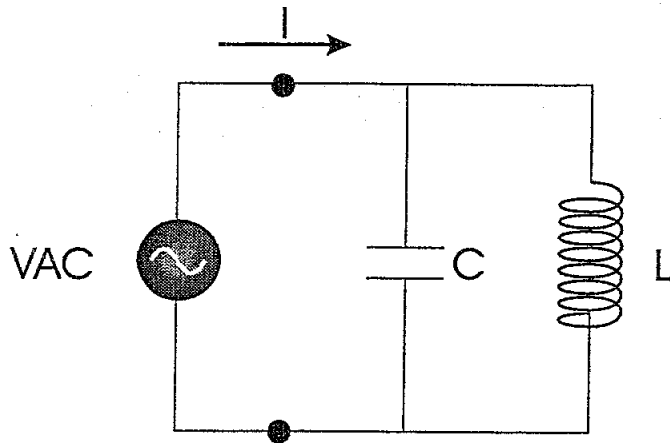


Figure 2.11: Capacitance in an AC Circuit

Power Factor Correction

A circuit with a power factor of one is said to have "unity power factor". Less current is required to supply a given kilowatt load at unity power factor than at low power factor. A capacitor can be utilized to cancel out the effect of inductance in a circuit, for the purpose of changing the power factor (Figure 2.12). This is called *power factor correction*, and the capacitor is called a power factor correction capacitor. By placing a capacitor in the circuit with an inductor we can create a balancing effect. The required capacitor size will depend on the amount of inductance and the frequency of the AC. Most practical circuits will have some resistance in the circuit, usually representing the electrical load. In this case the resistance also must be included in determination of the required capacitance for power factor correction.



What happens physically is; with the capacitance correctly placed, electrical power circulates between the inductance and capacitance, rather than between the inductive device and voltage source. If the capacitance is located next to the inductance, it frees the electrical system from the burden of circulating the power back to the source (e.g., the electrical power plant). Alternating current welding arcs like lagging power factor. This type of phase shift causes the voltage to be nearer its peak when current passes through zero, thereby helping to re-ignite the arc when the current's direction reverses.

Figure 2.12: Power Factor Correction

Electromagnetic Induction

If a magnet is moved quickly into a coil of wire, a voltage will be created known as “**induced electromotive force (EMF)**”. If the magnet is quickly removed, an EMF is also induced, but in the opposite direction. Where a magnet is held stationary and the wire is moved the same effect is created. The current caused to flow due to this induced EMF is called “induced current”. The phenomenon of an EMF induced in a conductor as it cuts or is cut by a magnetic field is called “electromagnetic induction” (Figure 2.13).

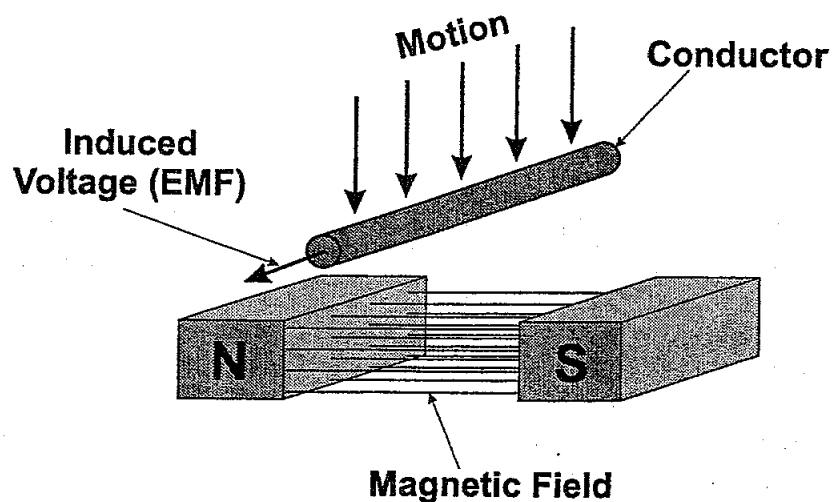


Figure 2.13: Induced Voltage (EMF)

The main factors which affect the amount of induced EMF are:

- the number of conductors in series (turns in a coil)
- the speed at which the magnetic field is changing
- the strength of the magnetic field

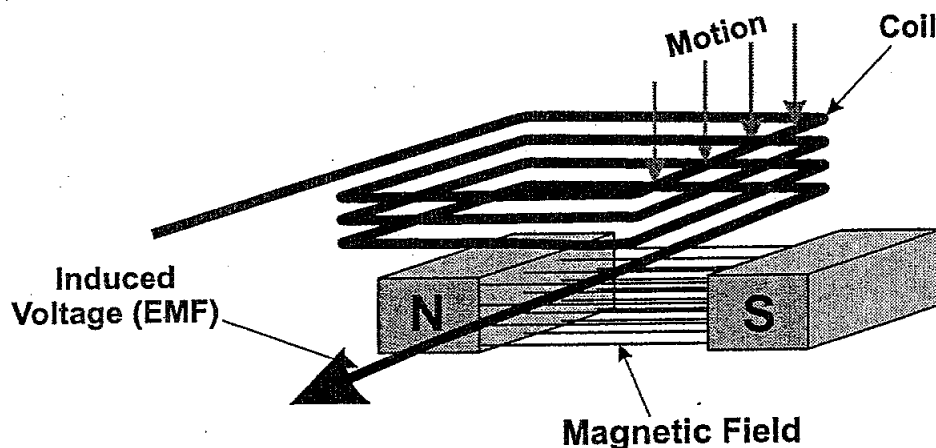


Figure 2.14: Induced Voltage in a Coil

The amount of EMF induced in a single strand of wire has limited uses. If we replace this single strand with a coil of wire greater EMF's can be produced. Each turn of the coil represents another conductor passing through the magnetic field. Each turn is of course in "series" with its neighbour and therefore the total EMF output becomes the sum of that produced in each turn (Figure 2.14).

When the speed at which a conductor moves through a magnetic field increases the amount of induced EMF increases. The amount of EMF induced is directly proportional to the speed at which the magnetic lines of force are cut. Therefore, it makes no difference whether the conductor or the magnetic field is moved.

The strength of the magnetic field affects the amount of EMF being generated. A stronger magnetic field has more lines of force than a weak field. If the coil is passed through a stronger field at the same speed it will be cutting more lines of force and the EMF induced will be greater. The magnetic lines of flux in the gap between the poles of a magnet are most closely packed at the center (Figure 2.15). Therefore passing the conductor perpendicularly between the poles of a magnet increases the effect of induction because the field strength changes more rapidly.

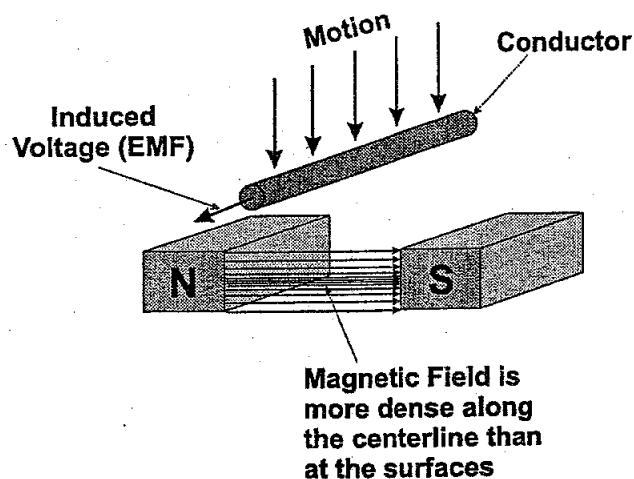


Figure 2.15: Magnetic Field Strength

The magnetic field could be produced in two ways:

- from a permanent magnet
- from an electromagnet composed of a ferromagnetic core wrapped with a current carrying coil of wire.

The magnetic field created by the current flow is intensified by the core and concentrated into the gap. The most powerful industrial magnets are electromagnets. Induction generators generally require a means to produce a magnetic field, and an electrical conductor in which the voltage is induced. Generating machines for producing electricity are based on this relatively simple concept of induction of a voltage in a conductor.

Rotating AC Generator

The rotating electrical generator was the natural implementation of the induction concept that quickly caught on in the development of electricity for practical use. Essentially, an electrical conductor is formed into loops and attached to a shaft. The shaft is rotated perpendicular to a magnetic field (Figure 2.16). This results in a voltage induced around the loops which varies as shown. The frequency of the sine wave, f , is determined by the rotational speed of the shaft. The simple generator in Figure 2.16 rotated at 3600 RPM would produce a sinusoidal frequency of 60 Hertz (cycles/second). Coils, rather than a single loop of conductor, are used to increase the voltage (each turn creates an increment in the voltage output). Sliding electrical contacts are required to pick up the voltage from the rotating conductors. This is accomplished with rotating rings and stationary sliding contacts called "brushes". This type of rotating electrical generator is called an AC generator.

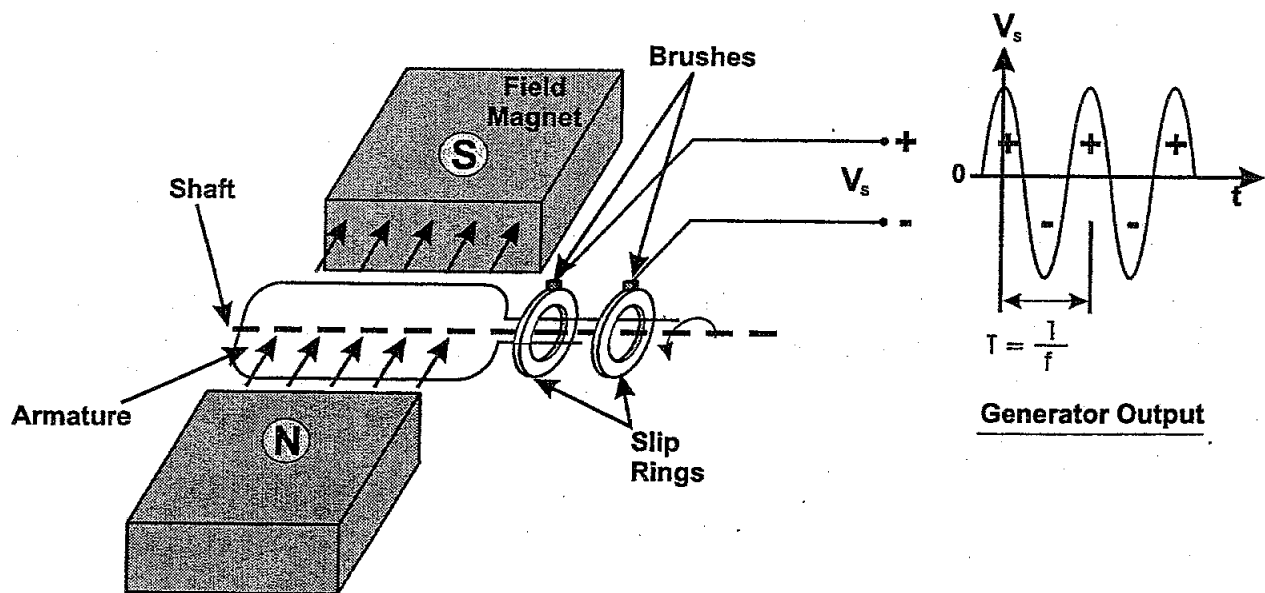


Figure 2.16: Rotating AC Generator

The conducting loop in which the voltage is induced is called the "*armature*". The element of the machine which produces the magnetic field is called the *field member* or *magnet*. In the case shown in **Figure 2.16**, the armature is also called the *rotor* since it rotates, and the field member is called the *stator* since it is stationary.

AC Alternator

A more robust variation of the AC generator principle is to utilize a fixed armature and a rotating magnetic field. A voltage is induced around the loops of the armature in exactly the same manner as an AC generator. The advantage is that the electrical connections to the armature may be fixed, and no sliding contacts are required. This is advantageous to the practical operation of a machine as current flow through sliding connections produces rapid wear and deterioration. The result is that alternator design requires less maintenance.

In actual implementations, the magnetic field member is rotated inside the fixed armature windings, producing essentially the same result in an even more effective design (**Figure 2.17**). Such machines are called *AC alternators*, or just *alternators*, and represent the practical design of modern rotating electrical machines for AC power generation. In this case, the armature is the stator and the field member is the rotor. The most common use of an alternator is on an automobile engine.

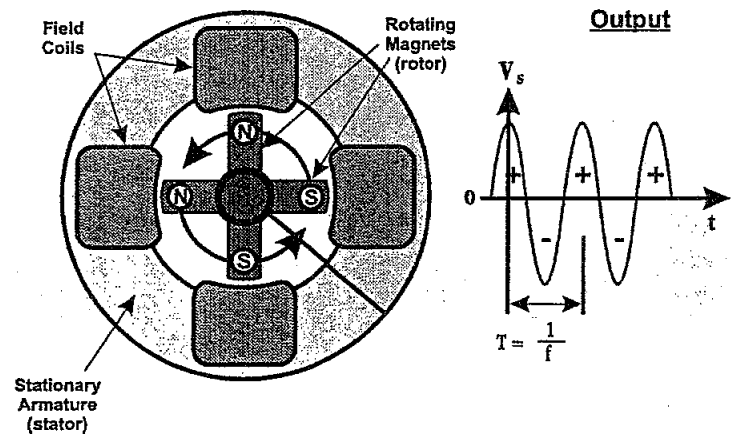


Figure 2.17: AC Alternator

Permanent magnets in portable welding equipment could create a reliability issue. Permanent magnets can lose their magnetism by shocks. Striking a permanent magnet with a hammer for example will cause its magnetic field to be lost. Portable welding equipment is often moved around construction sites in the back of a truck and this will present the opportunity for an equipment failure due to a loss of magnetism.

The field magnet in both the AC generator and alternator designs is usually created by an electromagnet rather than a permanent magnet as has been depicted. Therefore field windings and some current flow are required to produce the magnetic field. Since relatively low currents are required compared to the armature current, the required sliding connections are not a significant problem in the alternator design. The electrical source for the current in the electromagnet is called the *exciter*. Excitation may be obtained from a separate source (separately excited) or from the main generator output itself (self-excited).

DC Generators

Commutating switches can be utilized to *rectify* the sinusoidal waveform from an AC generator to produce a *rectified DC* as illustrated in Figure 2.18. The design of the commutator involves a rotating split ring and sliding commutator brushes. Refinement of such machines with additional ring segments allows the production of near DC output. Such machines are called *DC generators* or *dynamos*.

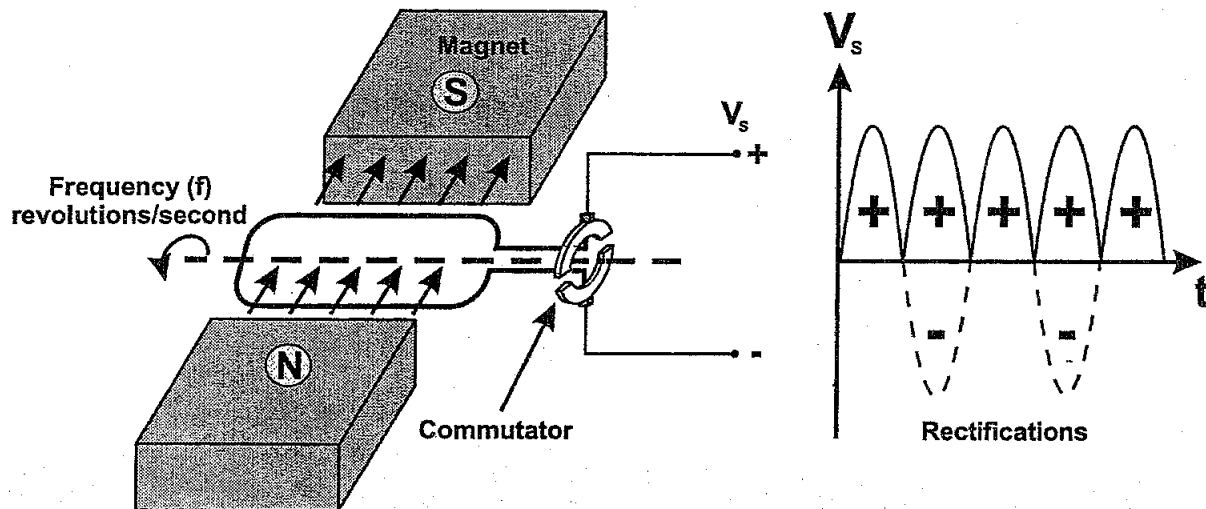


Figure 2.18: DC Generators

DC generators were widely used in the early days of electricity, including arc welding, where DC electricity was preferred. The main drawback of the DC generator is wear. The rings and brushes require frequent replacement. When brushes are replaced, a procedure called "stoning in" must be performed before welding can be allowed. The stoning process shapes the brushes to fit the commutator radius and prevents arcing. Rectification of AC from alternators utilizing rectifying diodes has superseded the use of DC generators in modern electrical power conversion for the production of DC voltage. (DC generators are still available and popular due to their high operator appeal.) An example of the change from the use of DC generators is in automotive electrical systems. In the 1960's, alternators with rectifying diodes built-in to provide a DC output replaced DC generators. Thus the term *alternator* for the systems used to produce DC voltage in automotive applications.

Multi-Phase Generators

The sinusoidal output of a simple AC generator or alternator is called "*single phase*". In modern electrical power generation, multiple, identical armature windings are commonly utilized so as to produce *multiple AC* outputs from a single alternator. These windings are typically spaced evenly around the armature such as to produce equally spaced "*phases*" of the electrical outputs. Three-phase alternators have the windings spaced equally such as to produce three sinusoidal waves each shifted by one-third cycle or 120 deg. (**Figure 2.19**). *Three-phase* is the standard for most power generation in Canada and the USA. A three-phase generator may be thought of as producing three separate single-phases, each identical except being shifted in time. Three phase power has a number of advantages, including the ability to connect phases in different ways to produce a range of voltages, and for use with equipment which is designed to operate efficiently from the three-phase supply. Residential electrical systems are single-phase, being derived from three-phase at electrical substations. Industrial power is usually delivered to the site and distributed as three-phase.

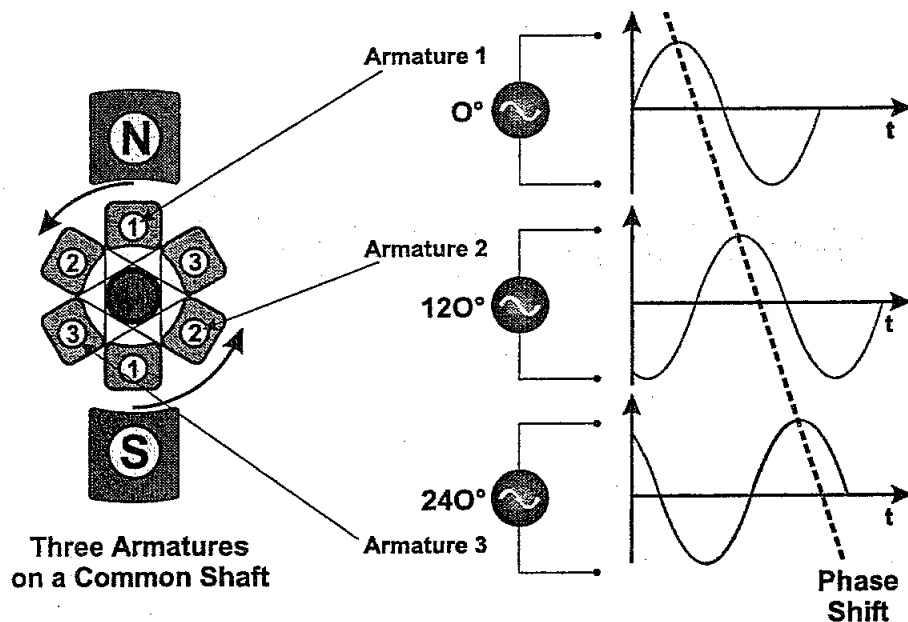


Figure 2.19: Multi-Phase Generators

Three-Phase Source Connections

Voltage from three-phase power generators are not typically transmitted with six wires - two for each phase (as might be envisioned). Instead, the sources are interconnected into three or four wire connections (**Figure 2.20**). One type of connection is called a *delta* and results in three wires. This connection is typical of long distance electrical transmission. The voltage between any two of the wires will be the voltage produced by the corresponding armature winding, called the *phase voltage*. A common connection for distributing three-phase power locally is the four-wire *wye* connection. Voltage

can be derived either between the middle connection and an outside connection (*phase voltage*), or between two outside connections (*line voltage*). The voltage between two outside connections is 1.73 times the armature (phase) voltage. This type of connection is commonly found in commercial/industrial applications where 120 volt single-phase is derived between center to outside connections, and 208 single- or three-phase is derived between the outer connections (U.S. and Canada). The center connection point is grounded to provide the neutral side of the single-phase connections. In heavy industrial applications, the phase voltages in the U.S. are commonly supplied at 277 volts and the line voltage is 480 volts. In Canada, phase voltages are commonly 347 volts with line voltage of 600 volts.

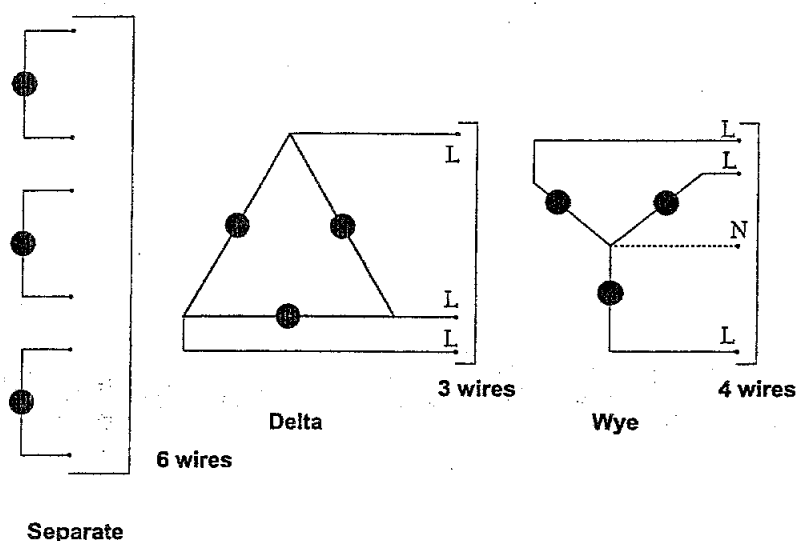


Figure 2.20: Three-Phase Source Connections

An AC source is connected to the *primary* coil of the transformer (**Figure 2.21**). An AC current flows in the primary coil as determined by its inductance, producing an alternating magnetic field inside the coil. The magnetic field is coupled to the *secondary* coil by the iron core. The alternating magnetic field inside the secondary induces a voltage around its turns, creating a voltage across the secondary coil. The secondary voltage is determined by the ratio of secondary turns to primary turns. Voltage can thus be transformed from one level to another.

Little power is lost in the transformer, thus RMS voltage times current at the secondary is only slightly less than RMS voltage times current at the primary. The small amount of power lost in the transformer occurs due to the resistance of windings and "eddy" currents induced in the iron core. The voltage generated in the secondary coil can also be expressed by the following equation:

$$V_2 = C \times (\text{flux density}) \times (\text{area of cross-section}) \times (\text{frequency } f) \times N_2$$

C is a coefficient related to core material.

Residential power in the U.S. and Canada is single-phase usually at either 115 or 208 volts.

Transformers

Transformers provide the main advantage for the use of alternating current for power systems. They provide a relatively simple means for increasing or decreasing AC voltage. With the use of transformers, voltages may be "stepped up" for transmission over long distances, and "stepped down" to suitable levels at the point of use. Welding transformers are typically "step down" transformers.

Transformers consist of two coils which function on the principle of *mutual inductance* (**Figure 2.21**).

A primary design consideration for a transformer relates to the frequency of the AC to be transformed. In essence, the inductance of the primary coil must be large enough that current drawn when there is no load on the transformer is small compared to its design current. At high frequency, the inductance is smaller with the same impedance. Thus transformer size decreases as the design frequency increases. Also, transformers normally are designed with the primary and secondary coils together rather than separate as depicted in **Figure 2.21**.

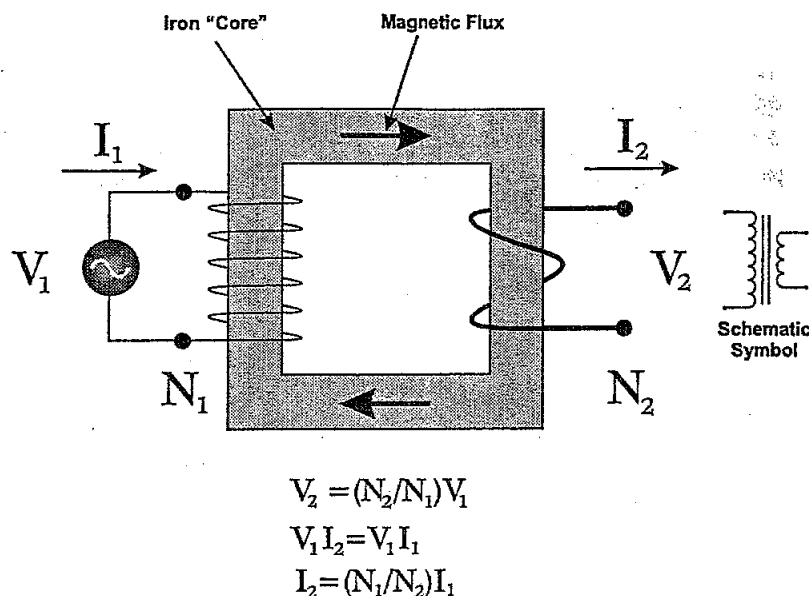


Figure 2.21: Transformers

Transformer Taps

Transformers are often supplied with *taps* that allow the transformer primary and secondary configurations to be adjusted. Taps provide connections to the transformer windings and when needed, intermediate points in the windings (**Figure 2.22**). The principle of step up or down relates to the "turns ratio" of the primary and secondary windings. If the secondary coil has one half the number of turns of conductor that the primary has, the voltage will be reduced by one half (step down transformer). The opposite is also true and for any combination of turns ratio's in between.

Primary taps are used to adapt the input of the transformer device to different AC line voltages while resulting in the same secondary voltage. A welding power source may have its primary connected to 600V, 460V, 230V or even 110V. The primary winding must have the correct connections at various numbers of turns to create the appropriate step down ratio for output voltage. Common industrial welding power sources require less than 80V open circuit for operation. Primary taps are usually fixed electrical connections.

The conductors of the secondary windings of a welding power source will be larger than the primary windings because of higher current handling. (high amperage/low voltage output).

Secondary taps are used to allow the output voltage of the secondary to be selected. For instance, a center tap will produce only one-half the voltage of the full secondary. Secondary taps may be fixed electrical connections, or may be in the form of switching that allows secondary voltage to be selected conveniently

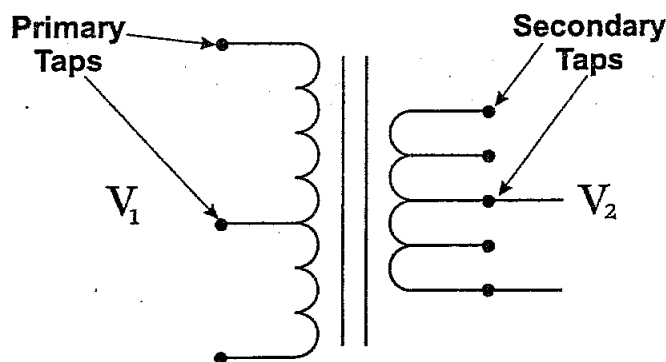


Figure 2.22: Transformer Taps

by a user. Secondary taps are sometimes used to provide adjustment of the power source output voltage, or voltage range.

The more modern variation of the tapped secondary voltage control system is the sliding contact secondary. (**Figure 2.23**). The outside of the secondary coil is lightly sanded to allow electrical contact between a brush and the coil. A mechanical system usually operated by a crank handle slides the brush along the secondary coil, changing the turns ratio and therefore the output voltage under a given load (wire feed speed). This system is commonly used for semi-automatic welding where constant voltage output is desired. A disadvantage of the system is the need for good electrical contact between the secondary coil and the sliding contactor. The sanded surface of the secondary coil can become corroded or covered in contaminants. These machines are frequently used within a narrow voltage range, depending upon the electrode/shielding gas/material thickness combination most commonly encountered. Poor contact occurs at the ends of the range of travel of the brush, where it seldom wipes the surface. To solve this problem, the coil must be cleaned to gently remove the surface deposits which are preventing good electrical contact. **Never work on welding machines with the power connected. Only properly qualified persons should work on welding machines.**

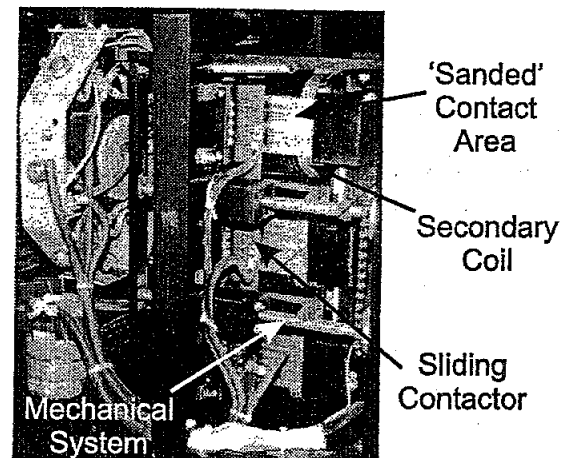


Figure 2.23

Solid-State Diodes

A transformer delivers AC power, but many welding processes require the use of DC power. *Diodes* are frequently used in combination with transformers to rectify the AC output from a transformer to provide DC.

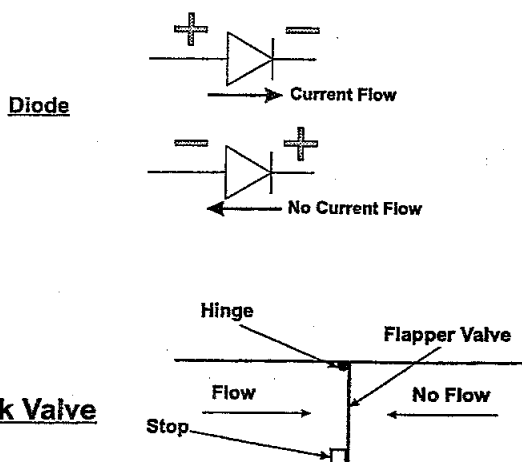


Figure 2.24 (a): Solid-State Diodes

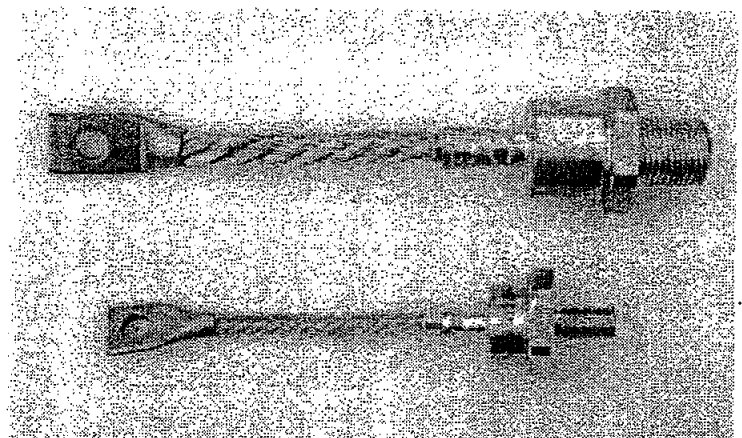
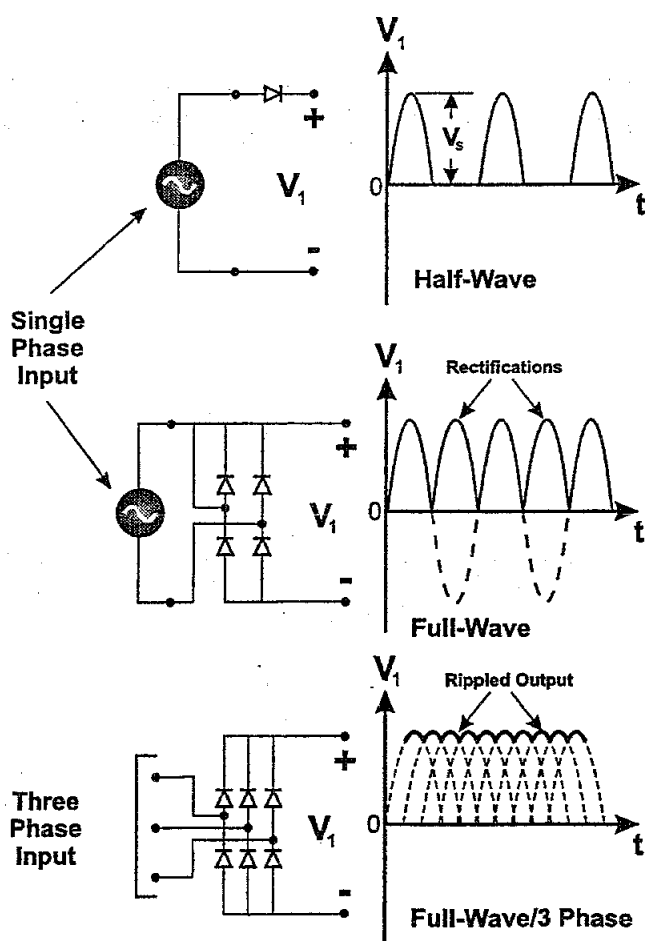


Figure 2.24 (b): Solid-State Diodes

Solid-state diodes are simple in operation. They conduct current in one direction with minimal voltage drop, but do not conduct significant current in the opposite direction. The arrow-like symbol for the diode indicates the direction of allowed current flow. Some energy is dissipated in the diode, and for high current applications provision must be made for cooling the diode by mounting onto a heat sink. A diode performs like a check valve in a flow system - allowing flow in only one direction (Figure 2.24).

Rectification of AC

Solid-state diodes allow *rectification* or *conversion* of AC to DC. A half-wave rectifier uses one rectifying diode to produce a single polarity DC as shown in Figure 2.25. This pulsating type of waveform has little practical use, but four diodes can be connected into a *rectifier bridge* to produce a *full-wave* rectified waveform, which includes both cycles of the AC. Three-phase AC can also be full-wave rectified with a six diode bridge to produce a much smoother DC output. The DC power produced in this manner is not smooth (as a battery) but has a "ripple" effect. Ripple is the variation in the voltage which results after rectification. It is usually desirable to have as little ripple as possible for most uses of the rectified voltage. Rectified three-phase has much less ripple than rectified single-phase. The ripple effect is shown in Figure 2.25.



Diodes designed for rectification applications are called *rectifying diodes* or just *rectifiers*. Before silicon diodes were perfected, rectification was accomplished with *selenium rectifiers*. These were more cumbersome, finned components, often found in vintage 50's and 60's electrical equipment.

Figure 2.25:
Rectification of AC

Section 3: Characteristics of Welding Arcs

Welding arcs are a type of electrical discharge, or electrical current flow in a gas, which is characterized by low voltage and high current. The observation of electrical arcs was common in the early days of experimentation with electricity. Arcs were usually a nuisance, occurring at electrical contacts when circuits were disconnected. Arcing of contacts causes their rapid deterioration and electrical circuits are designed to avoid arcing. As arcs were better understood, it became possible to create arcs under controlled conditions and develop applications for their use. Carbon electrodes were initially used for commercial lighting, producing the so-called *carbon arc*. The first arc welding process utilized a carbon arc and carbon arcs are still used in welding today but have largely been replaced by arcs operating with other electrode materials like tungsten, steel, or aluminum. An arc is a directional, highly concentrated heat source well suited to making a weld.

The purpose of this section is to provide an understanding of the physical nature of the welding arc, how it operates, and how its characteristics are used for different welding processes.

Conduction of Current in Solids and Gases

Electrical current is readily conducted in metals because electrons are in a free state. In essence, atoms are in intimate contact and can share electrons in a manner which actually allows some electrons to exist unattached to any atom. These free electrons can be imagined to be moving randomly at high speed, bouncing off the atoms in the wire. There are a very large number of free electrons in metals. For instance, a 1 mm cube of copper contains about 10^{20} free electrons. The free electrons are available to move *instantly* and produce current flow in response to the application of even the *smallest* electrical potential applied between end points of the conductor. Remember that since the electrons have a negative charge, they actually move in the opposite direction to conventional current flow (Figure 3.1). We can think of electrons in a wire as being like water in a pipe; when water enters one end of a full pipe, water immediately comes out at the other end.

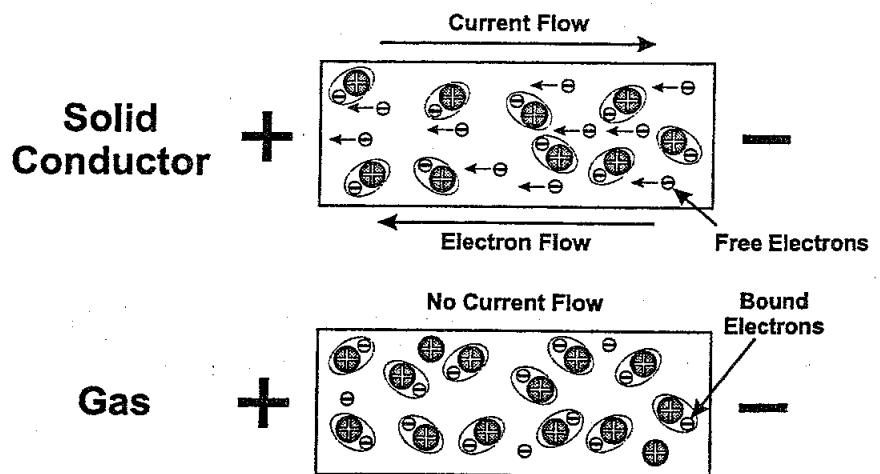


Figure 3.1: Conduction of Current in Solids and Gases

Normally electricity cannot be conducted through a gas. The atoms of a gas exist separately, and all of the electrons of an atom are tightly bound to its nucleus. Any atom of a gas can become a carrier of electricity by stripping it of one of its electrons - a process called "ionization".

Ionization

Ionization of an atom in a gas occurs when a sufficient amount of energy is imparted to the atom to "break off" an electron, creating a free electron and a positively charged nucleus (ion). The creation of these charged particles leads to the possibility of current conduction (Figure 3.2).

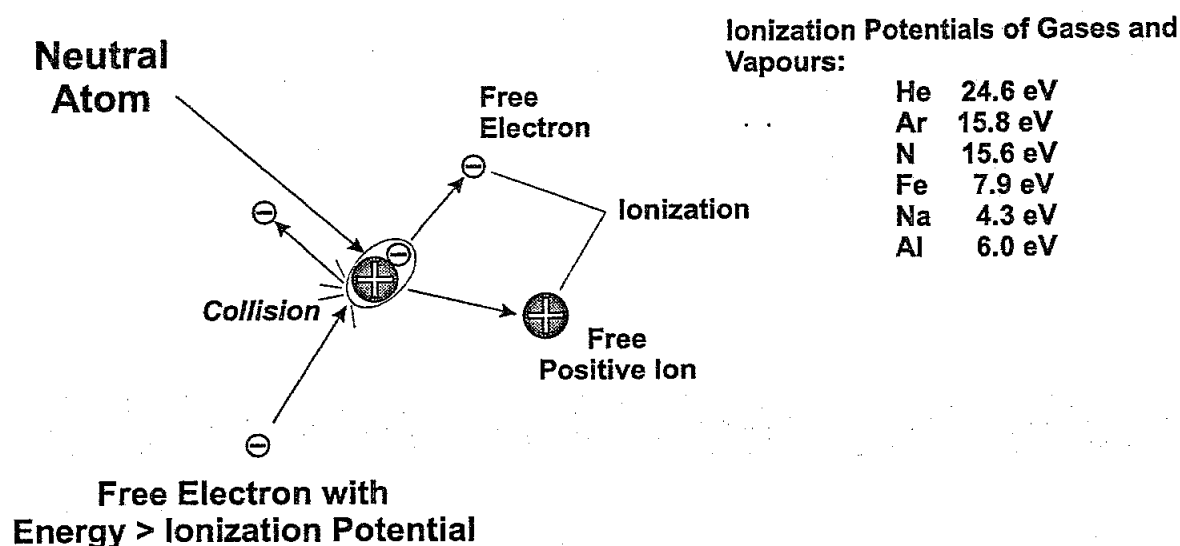


Figure 3.2: Ionization

The *ionization potential* of an element is the amount of energy that must be imparted to the atom in order to create an ionization. The energy for ionization is usually imparted by collision of an already free electron with an atom. The free electron must have a kinetic energy greater than the ionization potential of the atom it impacts. The ionizing electron's energy is usually gained from acceleration in an applied electric field (potential). Most gases, in fact, have a very small amount of ionization already present which helps the establishment of a conductive path when a sufficient voltage is applied.

Ionization potential is measured in *electron volts (ev)*, sometimes referred to only as *volts*. For instance, the ionization potential of argon is 15.8 electron volts. The unit of electron volts is convenient from a physical standpoint since it expresses the number of volts that an electron would have to be accelerated through to achieve that much kinetic energy. If an electron were accelerated in a vacuum between two electrodes with a voltage difference of 15.8 volts, it would pick-up enough kinetic energy to ionize an argon atom.

Atoms with higher ionization potentials are more difficult to ionize. Inert gas atoms generally have relatively high ionization potentials (10 electron volts and higher). Metal atoms, which occur as metal vapors in the arc, generally have low ionization potentials (less than 10 electron volts). Metal vapors thus lend themselves to ionization in the arc. In metal arc processes low ionization potential additives are made to fluxes and coatings to promote arc initiation and improve arc stability.

Electrical Breakdown

A gas can become a conductor under the unusual condition of so-called *electrical breakdown*. Electrical breakdown of a gas results from the application of an electrical potential or voltage across the gas. The voltage is applied to the gas via metal conductors, or electrodes, placed in the gaseous media. A gas will break down electrically and be able to conduct current when sufficient voltage is applied. The minimum voltage needed to create a conductive path is called "sparking voltage". Sparking voltage increases with the pressure of the gas, and the distance or gap between the electrodes. The sparking voltage is also dependant on the electrodes' composition, surface finish and especially the shape. Flat or slightly curved electrode surfaces generally require more voltage for breakdown compared to sharply pointed electrodes.

Sparking voltages are typically 1000's to 10,000's of volts. Larger gaps require proportionally higher voltages, as do higher pressures. Arcs therefore require higher voltages to initiate with wider gaps and at higher pressures (e.g., underwater). The composition of a gas media influences the voltage required to initiate the arc. Higher voltage is required to initiate an arc in helium than in argon due to helium's higher ionization potential.

Welding power sources are designed to initiate arcs in several ways. Jumping an air gap by sheer current would require 1000's of volts - it would be far too dangerous. Initiating the arc is usually accomplished in two ways; impose a momentary high voltage, low current surge accross the gap or by "striking" the electrode against the work surface, essentially producing a very short gap. Initiating the arc is more difficult than sustaining it.

Conduction of Current in the Arc

After breakdown of the gas in the arc gap is created, current flow through the gas commences (**Figure 3.3**). The conductive path will widen as more electrons are emitted and collide with gas atoms in the gap. Electrons are much lighter than ions therefore they pick up speed and energy more rapidly when propelled through the gap by the applied voltage. This is accompanied by intense resistive heating of the gas through collisions with the accelerating electrons, and the gas temperature rises. As the gas heats up, *thermal ionization* maintains and produces more ionization, which reduces resistance in the arc and current flow increases. Thermal ionization is additional ionization created by collisions of ionized particles with neutral atoms causing the neutral atom to lose an electron. See **Figure 3.3**.

If the source supplying the voltage is capable of suitably delivering the rising current demanded by the arc, then a stable mode of current flow is reached which is called an arc. At atmospheric pressure, this means that the power source must be able to deliver tens to hundreds of amperes at several tens of volts. If the power source cannot deliver current under these conditions, then only an instantaneous spark occurs and the arc will not be sustained.

The temperature of gasses in the arc typically rise to 10,000K and higher as the arc develops. These temperatures are considerably higher than that of any other type of heat source, being well above temperatures achieved in conventional resistive heaters or open flames. The very high temperatures are necessary to sustain the ionization process. The hot, ionized gas of the arc is sometimes referred to as a *plasma*.

Electrons are emitted from the negative electrode (cathode) travel through the arc and are reabsorbed by the positive electrode (anode). The electrons collide with neutral gas atoms creating additional free electrons and positively charged gas ions.

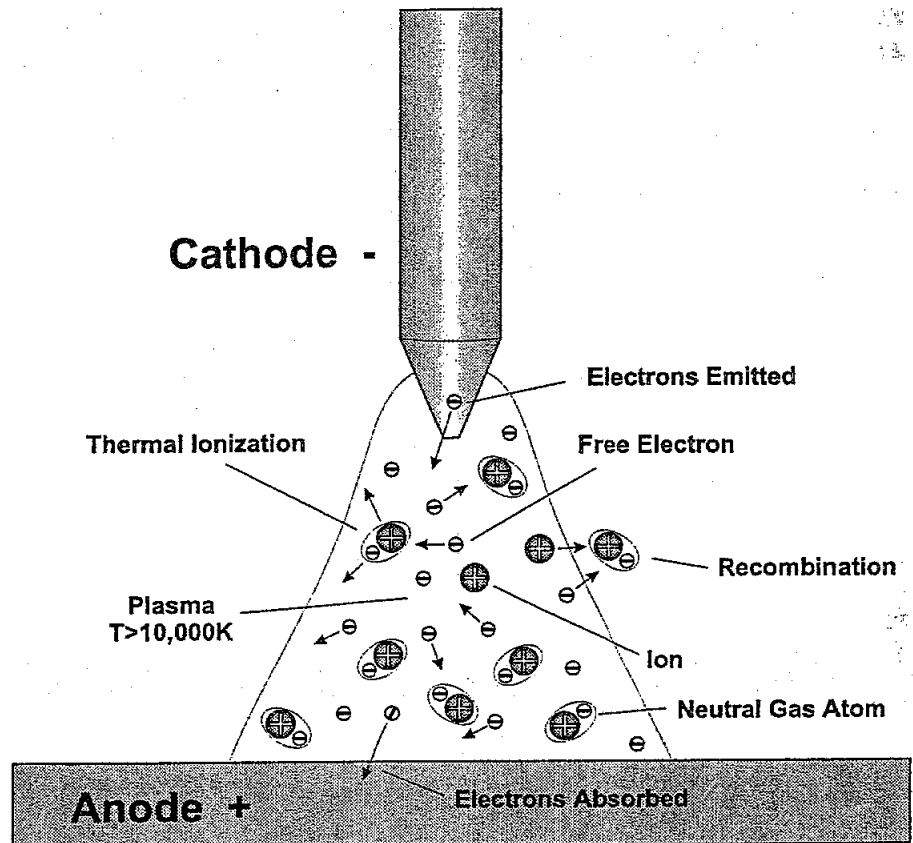


Figure 3.3: Conduction of Current in the Arc

Polarity and Current Flow

Welding arcs are usually operated on direct current (DC), with fixed polarity or voltage between the electrodes. The *welding electrode*, or *electrode*, is either positive or negative, and the *work lead*, or *work*, is of opposite polarity. If the electrode is operated with negative polarity relative to the work, this is called *DC Electrode Negative* or *DCEN*. The older terminology was *Straight Polarity* or *DCSP*. In this case, electrons carry the electrical current from the electrode to the work. The electrode is the cathode and the work is the anode. The polarity can be reversed making the welding electrode positive, this is called *DC Electrode Positive* or *DCEP*, also known as *Reverse Polarity* or *DCRP*. In this case, electrons carry the current from the workpiece to the welding electrode. The work is the *cathode* of the arc (emits electrons), and the electrode is the *anode* of the arc (receives electrons).

The difference in electrical processes at the anode and cathode influence the performance of the arc relative to its welding application. Some arc welding processes are operated predominately with a certain polarity (GTAW – electrode negative, GMAW – electrode positive), and some can be operated with either polarity (SMAW – electrode negative or positive, depending on coating composition). Alternating current or AC is used in some process variations and the polarity alternates between electrode negative and electrode positive. The AC voltage is usually derived directly from the AC line, thus resulting in a 60 Hertz rate of alternation. In more sophisticated inverter power supplies higher frequencies may be utilized. Alternating current may be used for simplicity and economy in equipment, or for the special effects of alternating polarities.

Arc Voltage-Amperage (V-I) Characteristics

The graphical method of presenting voltage-current characteristics is very useful for the study of welding arcs. The voltage-current characteristic of an arc can be found by measuring arc current and voltage for different power source settings, while holding *arc length constant*. This is simple to perform with a tungsten arc - more difficult for arcs in consumable electrode processes. The resulting curve is shown in **Figure 3.4**. A resistor, which obeys Ohm's law, would appear as a straight line. Arcs differ greatly from the linear characteristic of the ideal resistor. The nonlinear characteristic of the arc makes graphical V-I analysis of arc circuits helpful in understanding their operation.

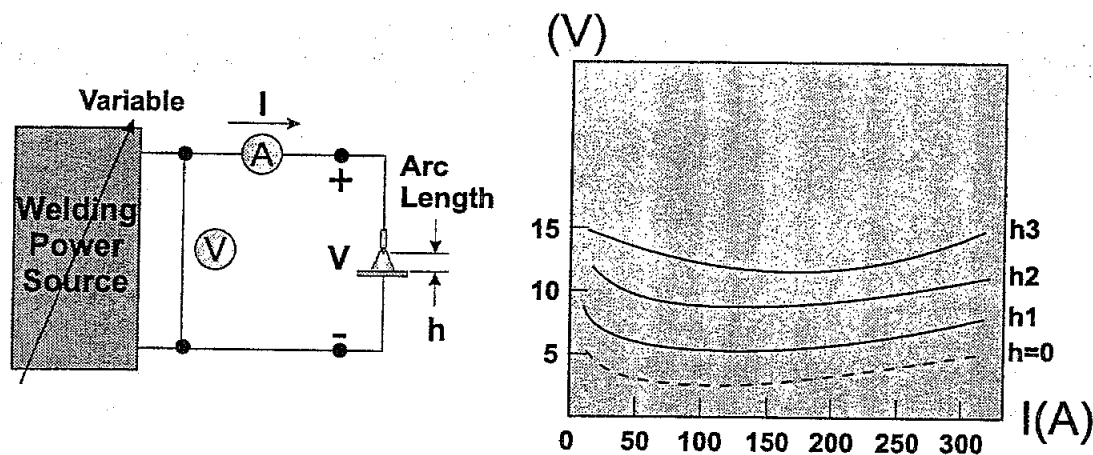


Figure 3.4: Arc V-I Characteristics

At low current the curve is drooping. The characteristic rises to a high voltage at zero current because of the voltage required to create a conductive path across the gap. At intermediate current levels the curve is quite flat, almost operating at a constant voltage independent of current. The voltage to operate the arc drops with increasing current to around 100 amperes and then rises at a slow rate. This *constant voltage* tendency of the arc operating at intermediate current levels is one thing that makes it an unusual electrical load (within typical voltage ranges and arc lengths). At high current the arc demands increasingly greater voltage to remain stable.

Process Polarity

There is a significant difference in the way in which electrons are generated between non-consumable electrode processes such as GTAW, and consumable electrode processes such as GMAW. The GTAW process is usually operated with the electrode negative. Electrons are easily emitted from the solid tungsten electrode, and transfer energy to the weld pool as they condense at the workpiece surface. Gas tungsten arc welding does not operate well in the electrode positive mode. Electrons transferred from the workpiece impart large amounts of energy to the electrode tip which, tends to cause melting. However, the GMAW process operates best on electrode positive as the process tends to be unstable in electrode negative mode. Electrode positive produces a stable arc with good penetration (See Module 4).

Arc welding processes are operated in alternating current mode. The simplest welding power sources are step-down transformers with no rectification mechanism - a functional and inexpensive power source. Alternating current presents a problem for maintaining arc stability since the arc tends to extinguish as the power flow reverses between each half cycle. Aside from a momentary lack of current flow through the arc, there are differences between the emissivity of the tungsten and the workpiece. Tungsten, especially tungsten electrodes alloyed with oxides of readily ionizable elements (thoria, ceria, lanthana), much more easily release their electrons to the arc stream than the workpiece. This creates a momentary "hesitation" in electron flow as the polarity reverses and the work becomes the negative pole. A consumable electrode alternating current arc (SMAW) required the development of additives to electrode coverings which provide arc stabilization. Coating additions of easily ionizable materials enhance the persistence of ionized gas particles as the voltage passes through zero.

An advantage of AC is that it produces heating effects in between that of DCEN and DCEP. Alternating current also lessens the occurrence of magnetic arc blow at high welding currents, and is therefore useful in high deposition applications of SMAW and SAW.

AC is also used to great benefit in the GTA and Plasma (PA) welding of aluminum and other similar materials which form a refractory oxide. During the electrode negative cycle, heat and penetration into the material being welded is promoted. Electrode positive provides oxide removal by cathodic action at the work. Alternating current GTA welding is commonly used for aluminum (See Module 4). More advanced AC machines provide a square rather than a sine wave AC, to improve arc re-ignition capability. Variable polarity of AC allows for adjustment of the duration of positive versus negative cycles. Inverter based power supplies offer the potential to increase alternating current output frequency which offsets defocusing effects on the arc column.

Section 4: Process Characteristics and Power Requirements

Gas Tungsten Arc Welding

The gas tungsten arc welding (GTAW) process uses a non-consumable tungsten-based electrode. Arc length is either under the control of the operator or of the mechanical system in the case of mechanized welding. A constant current power supply is used, and current is set at the power supply. The arc gap is controlled by the welder in manual welding, and by the machine in mechanized welding. Voltage across the arc is determined by the arc gap and the shape of the end of the tungsten electrode. Since current is held approximately constant, small changes in arc gap and voltage do not produce large changes in current. In practice, most power supplies have a characteristic which approximates to constant current called a "drooping" characteristic. Some modern power supplies with electronic control systems are able to operate with true constant current.

Plasma Arc Welding

The plasma arc welding (PAW) process is based on constriction of a tungsten arc through an orifice in a copper nozzle (See Module 4). The torch is designed with a small chamber surrounding the electrode where the ionized gas is prevented from expanding freely. This causes a superheating effect and the superheated plasma is directed out of the chamber through an orifice creating a plasma "jet". Because of the jet that is produced, the process is less affected by arc length changes. The increased plasma pressure and energy allows the process to operate in the keyhole mode, where the plasma jet creates an open "keyhole" completely through the joint. The process is normally operated in the *transferred arc* mode, where the arc is formed between the electrode and workpiece, and is constricted by the orifice. In this mode the power requirements for the main arc are very similar to those for GTAW, and GTAW power sources can in fact be used to supply the power for the plasma arc. However, in order to start the process, a *pilot arc* at low current/high voltage is created between the electrode and the copper nozzle. This provides an ionization source, which enables the main arc to initiate when the circuit between the electrode and work piece is completed - the arc is thus *transferred* from the copper nozzle to the workpiece. A separate power supply can be used to maintain the pilot arc, and a high voltage/high frequency or impulse start is used to enable the pilot arc to initiate. Systems of this type are available as "add-on" units to convert a GTAW system to plasma welding. Modern control technology allows a single power supply to be used both for the pilot arc and for the main arc.

Keyhole welding requires welding current in excess of 100 amps. However, plasma welding can be performed in melt-in mode and provides a very precise source of heat for welding small components at very low current, from 0.1 to 15 amps. This variant of the process is called *micro plasma* or *needlearc*. At these low current levels, a transistor-based design is often used with electronic control to provide true constant current characteristics.

Gas Metal Arc Welding

In the early development of gas metal arc welding (GMAW), constant current power sources were used. However, with a constant current output, a change in contact tip to work distance will also produce a change in arc length for a constant electrode feed rate. As a result, the arc will either *burn back* (fusing the wire to the contact tip) or stub into the workpiece. To avoid this problem, voltage controlled wire feeders were developed, where the wire feed speed increases if the voltage increases (indicating a longer arc) in order to hold arc length constant.

It was then found that a constant voltage power supply could be used with the GMAW process. With a constant speed wire feeder, the slope of the power supply acts to compensate for changes in contact tip to work distance - the system is thus self compensating, and does not require feedback of the arc voltage to the wire feeder.

The GMAW process can be operated in several modes: In the short circuit mode, the wire intermittently touches the workpiece, and a *short circuit current* flows at zero voltage, until the wire is melted, detached and the arc is re-established. In this mode of operation, either changes in slope or other controls are used to achieve an appropriate short circuit current: high enough to re-establish the arc, but not so high that the wire melts explosively producing excessive spatter. The *rate of change* of current is also important in controlling the performance of the arc. Rate of current change is controlled by adjusting the amount of inductance in series with the power source, (either as a stepped or continuously variable inductance). Electronically controlled output of the power supplies may use either inductance or electronic control to adjust current rise rate.

At higher currents, the GMAW process operates in the *spray transfer mode* where an arc is maintained continuously, and metal is transferred as droplets from the wire across the arc to the workpiece. The slope of the volt ampere curve, and the rate of current rise are again important to achieve stable arcs with minimal spatter, and must be matched to the wire type, diameter and shielding gas used.

Flux Cored Arc Welding

The flux cored arc welding (FCAW) uses a tubular electrode which contains powdered flux, and may be applied with or without shielding gas depending on the flux formulation. The electrical characteristics of the process are in very similar manner to GMAW and essentially the same equipment is used.

Submerged Arc Welding

The submerged arc welding (SAW) process can be used manually, with wire diameters in the range of 1.6 to 2 mm, and current in the range of 250 to 500A. It is more commonly used in mechanized applications, with large wire diameter (4 to 4.8 mm) and current in the range 475 to 900 amps. Although two small wires fed simultaneously from the same welding head is a common variation. Several different types of power sources can be used with submerged arc welding. *Constant voltage* DC power sources are available with rated output from 400 to 1500 amps. A 100% duty cycle power supply is needed for mechanized application. The smaller power supplies can be the same as those for GMAW and FCAW. Constant voltage power supplies are self regulating, and are used with a constant-speed wire feeder. Voltage is set by adjusting the control on the power supply, and the wire

feed speed setting determines the current which will be drawn.

Constant current power supplies can be used, both DC and AC, but they are not self regulating, so they must be used in conjunction with a voltage sensing variable wire feed speed control which adjusts wire feed rate in response to changes in arc voltage. In this system, the power source outputs steady current, and arc voltage is maintained constant by the regulation of wire feed speed. Modern AC power supplies, used for GTAW, deliver square wave AC waveforms to avoid arc re-ignition problems as the current goes through zero while reversing. AC welding is most commonly used for high current applications, over 1000 amps, where arc blow can be a problem, and for multiwire applications to prevent arc interaction.

Shielded Metal Arc Welding

Either DC electrode positive, electrode negative, or AC power sources may be used for shielded metal arc welding (SMAW). Transformer rectifier machines often have a switch to change between DC and AC welding. Portable constant current power supplies often have a selectable range of sloped output. Steep slope minimizes the change in current from changes in arc length - constant current. In some situations a flatter slope is used to provide some change in current when arc length changes. Skilled welders can use this effect to achieve control over the current and hence the amount of metal being deposited. This is a common preference when manually welding pipe joints.

The table below shows a summary of the power type requirements for each welding process.

Welding Process	Constant Voltage DC (Flat Characteristic)	Constant Current DC (Drooping Characteristic)	AC (Drooping Characteristic)
GTAW	No	Yes	Yes
PAW	No	Yes	Special applications
GMAW	Yes	Yes	Special applications
FCAW	Yes	Yes	Special applications
SAW	Yes	Yes	Yes
SMAW	No	Yes	Yes

Table 4.1: Summary of Process Requirements

Section 5: Arc Welding Equipment Design

Early Power Source Technologies

Historically most welding was accomplished manually, where the arc was controlled by the welder. Power sources had to be the constant current, or drooper variety because it is nearly impossible to control a constant voltage arc, manually. It was also necessary to provide for variation of the current so the welder could adjust the amount of heat and metal deposition. Current control required the design of special power source circuits, the technology of which has advanced gradually with time and now dramatically over the last decade. The development of constant voltage power sources for automatically fed electrode processes have experienced similar developments, but over a shorter span of time and technology.

An arc is an unusual sort of electrical load. For most purposes the voltage supplied to electrical devices is designed to be more or less constant regardless of current demand. Conversely, an arc requires comparatively higher voltage to facilitate striking but, only low voltage in operation. Therefore the term drooping output; where voltage drops rapidly with increasing current flow. In **Figure 5.1**, the arc voltage demand drops quickly as current increases and rises only slightly even with large increases in current.

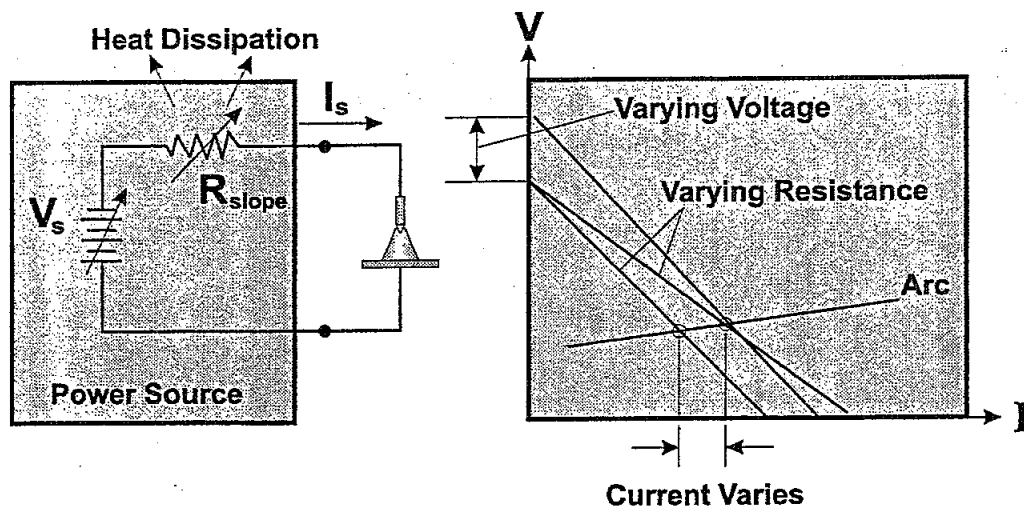


Figure 5.1: Early Power Source Technology Using Batteries and a Resistor

The earliest welding power supplies used lead-acid storage batteries, with a variable resistance placed in series to provide this output slope control (e.g., traceable to the original invention of arc welding in the 1880's). Banks of lead-acid batteries were used, charged by a DC generator, and provided direct current for carbon arc operation. A bank of resistors was used to provide slope and a rheostat type control of welding current. The resistance produces the output slope or droop of the power source. As the resistance is increased, the voltage drop across the resistor is reduced and so is the current flow in the output circuit. Either the amount of resistance, or the number of batteries connected in series, was used to control the amount of current. More batteries or less resistance increased the current output. A major disadvantage of the use of resistance to control current is poor efficiency. A large amount of

power is dissipated in the series resistance to no useful purpose. If the batteries supply 80 volts, and a drop of 20 volts occurs across the arc, 75% of the power will be dissipated in the series resistance, and only 25% is used in the arc. A constant current source requires high *open circuit voltage* both for arc starting, and to achieve a drooping output characteristic. Commercial usage of arc welding quickly shifted away from this type of power supply.

DC Generators

Early developers found that specially designed DC generators could be used to create arcs directly. In such designs some field windings in the generator are put in series with the welding output. The windings are connected such as to decrease the magnetic field of the generator as output current increases (so-called series bucking windings). This causes the output voltage of the generator to drop with increase in current, or to droop (**Figure 5.2**). This design accomplished droop without large, wasteful resistors and thus with much greater efficiency. Direct current generators have improved in design and are still used as sources of welding power. Generators of early vintage were driven either by engines in portable applications, or by AC electrical motors in shop applications. The latter were called motor-generator or MG-sets. Modern DC generators are used primarily in mobile applications with diesel or gasoline engines.

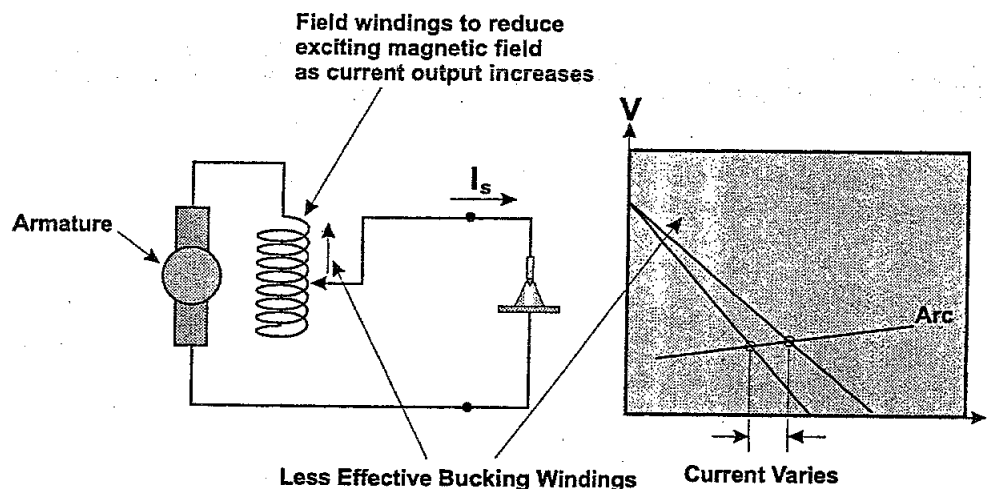


Figure 5.2: DC Generators

Motor-generators are not widely manufactured for welding power supplies due to their high cost and increased maintenance requirements, but are still in use in many operations. They are strongly favoured by certain industries, especially for pipe welding. The preference by the welder/operator is due to the intrinsic reactance created by a copper coil spinning in a stationary magnetic field. An objective of early electrical designs for replacing generators with transformer/rectifiers was to produce arcs as good as those produced by motor generators. Most manufacturers of engine driven welders use AC alternators with more conventional circuits for conversion of alternating current to direct current. **Figure 5.3** shows a modern alternator type, engine driven welder for DC or AC welding at 25 to 250 amps with SMAW, GTAW, GMAW, and FCAW which produces welding arcs with very desirable characteristics. Disadvantages of motor-generators are that they are bulky and heavy, have many

moving parts which are prone to wear and require frequent maintenance, and are noisy.

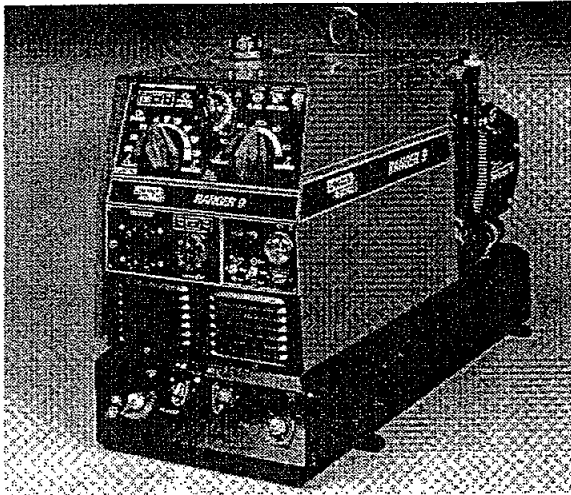


Figure 5.3: Engine Driven AC/DC Alternator Type Welder

(Photo courtesy of Lincoln Electric Co.)

Welding Transformers

The use of AC utility power for the direct production of an arc rather than with an electric motor/generator set requires a transformer. A transformer (**Figure 5.4**) is an alternating current device used to convert high voltage line power to safer, useable low voltage levels at the higher current levels needed to sustain a welding arc (**See Section 2**).

This basic conversion process is accomplished with a "step down" transformer. Such a transformer utilizes a large number of turns of relatively small size wire on the primary (high voltage/low current) side, and a lesser number of turns of larger size wire on the secondary (low voltage/high current) side. The resulting output voltage is a function of the "turns ratio" of primary/secondary windings. Magnetic flux is coupled from the primary to the secondary windings of the transformer by a massive iron core. The transformer is the central element and, to a great extent, dictates the size and weight of the power source.

In the simplest of designs, a welding power source consists only

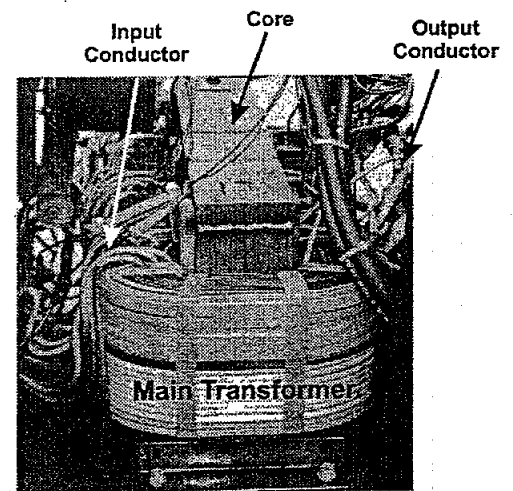
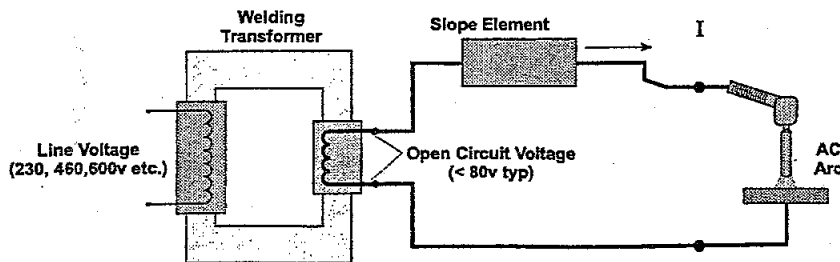
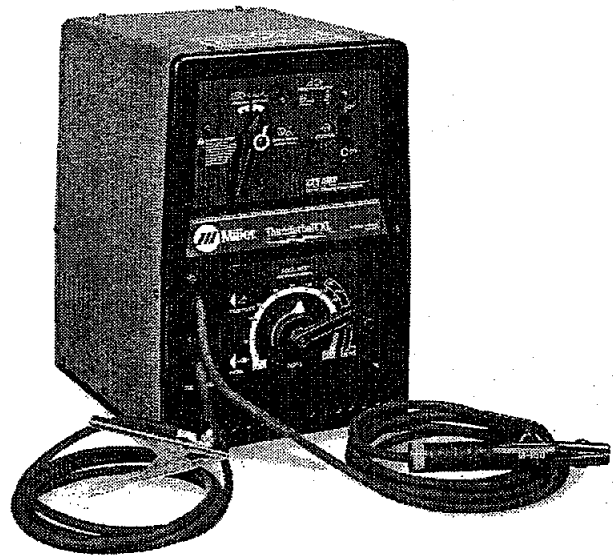


Figure 5.4: Welding Transformer
(Courtesy of Hawkes Electric Arc)

of a transformer to provide an AC secondary output with suitable capacity to operate a welding arc. the sloped output characteristic is accomplished by the manner in which the transformer is wound and the size and shape of the core. Older terminology sometimes refers to a welding power source as just a "welding transformer". Modern welding power sources are much more than just transformers, although it is the most fundamental element of even the latest of welding machines. **Figure 5.5** shows a transformer-based AC welder for SMAW welding, with rated output of 225 amps at 20% duty cycle and 100 amps at 100% duty cycle. The crank handle indicates that this is a mechanically controlled transformer. There are several means of controlling the output of a transformer, and the simplest method is to change the efficiency of "coupling" between primary and secondary. Moving the primary coils away from the secondaries reduces the number of lines of flux which pass through the secondary coils - reducing output by changing the effectiveness of coupling. The same effect can be created by moving part of the core to increase or decrease the strength of the magnetic field coupled to the secondary.

Figure 5.5: Transformer-Based AC Welder for SMAW

(Photo courtesy of Miller Electric Manufacturing Company)



Transformer Rectifier Technology READ

A rectifier is a device for converting alternating current to direct current. The development of solid-state rectifiers, first using selenium diodes and then silicon diodes, was a significant development for the use of AC transformer technology since it allowed a transformer based power supply to output direct current. (Without a rectifier, transformer welders can only produce AC current.) In general, alternating current results in inferior welding performance for most welding processes (excluding SAW) compared to that with DC. This power source technology is referred to as a "transformer-rectifier". All modern welding machines utilize these basic components in their circuit design (**Figure 5.6**).

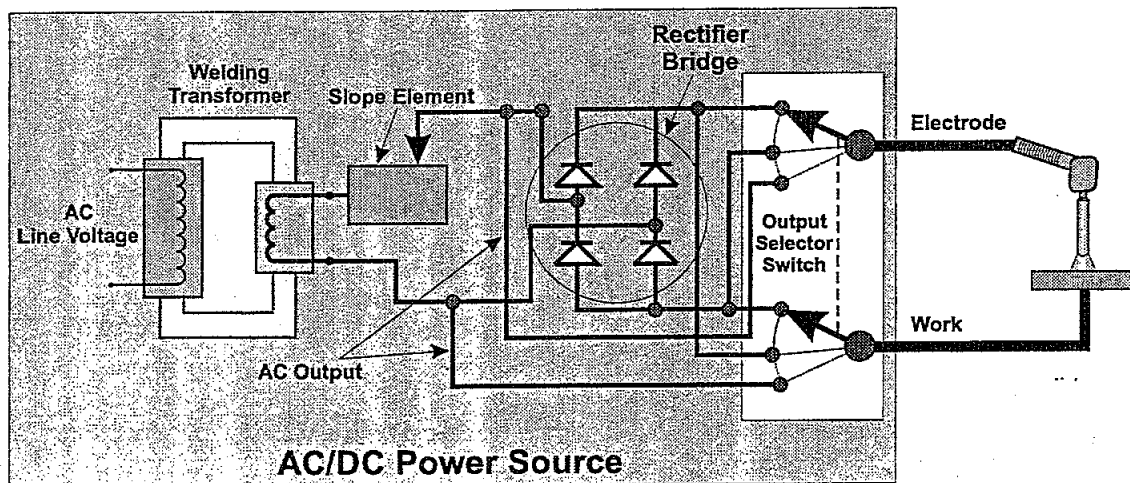
Conventional transformer- rectifiers, rectify AC current on the secondary side of the transformer, at lower voltage and higher current. The reduction in voltage must be accomplished prior to rectification since the transformer is strictly an AC device. (Only outputs when the magnetic field is changing).

Rectification can be applied to single-phase AC to give a single-phase type of rectified waveform. Such single-phase transformer-rectifier machines are often supplied as AC/DC machines, where the rectifiers can be by-passed to allow AC to also be delivered. A disadvantage is that single-phase rectified DC is very ripply, and does not produce the most desirable DC arc. This effect can be

reduced by adding capacitors into the output circuit.

Rectified three-phase is preferable for the operation of DC arcs. The overlapping of the phases eliminates most of the ripple and produces a more uniform and stable arc. (See Section 2) Also, the input line current is reduced since it is divided between the three-phases.

Figure 5.6: Transformer Rectifier Technology

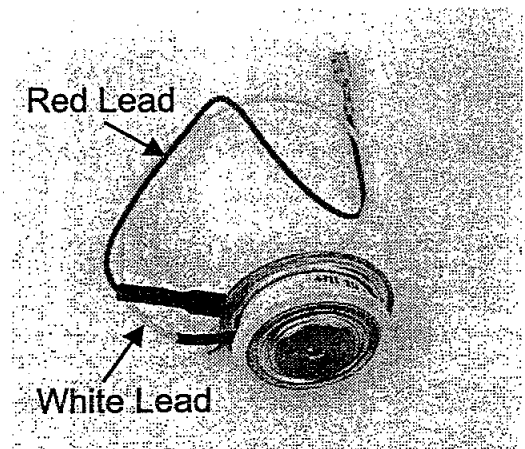


Silicon Controlled Rectifiers (SCR) - Thyristors READ

A conventional diode placed in a circuit allows passage of current in one direction only. Anytime a voltage is applied in the correct direction, the diode will allow the passage of current. (see Section 2) A silicon-controlled-rectifier (SCR) or thyristor operates slightly differently. The device still behaves as a diode - allowing passage of current in one direction only - but must be switched on to allow current to flow. A thyristor is activated by a signal called a "gate pulse" and will conduct current in the direction of its bias until the AC half cycle is complete. At the completion of the half cycle, voltage drops to zero and then reverses direction (Figure 5.7).

Figure 5.7: Pancake Type SCR (white lead is the gate, red lead is DC power for pc board)

In the opposite direction the thyristor acts like a diode and does not allow the passage of current. Each time a new



cycle starts the thyristor must be "gated or fired" again to allow passage of current. This switching or gating feature allows for output control, which is adjustable 120 times per second (line frequency 60). For example, if the thyristor is *gated or triggered* part way through a half cycle, then it will conduct to the end of the half cycle (**Figure 5.8**). This allows the time of forward conduction (current flow) to be controlled, and therefore the average output of a rectifier bridge. SCR's require special control circuits to provide the trigger or gating signals between the negative terminal and the SCR gate. The SCR therefore acts both as a rectifier to generate DC, and as a control system to regulate power output. **Figure 5.8** shows the operation of a half wave SCR rectifier controlling voltage.

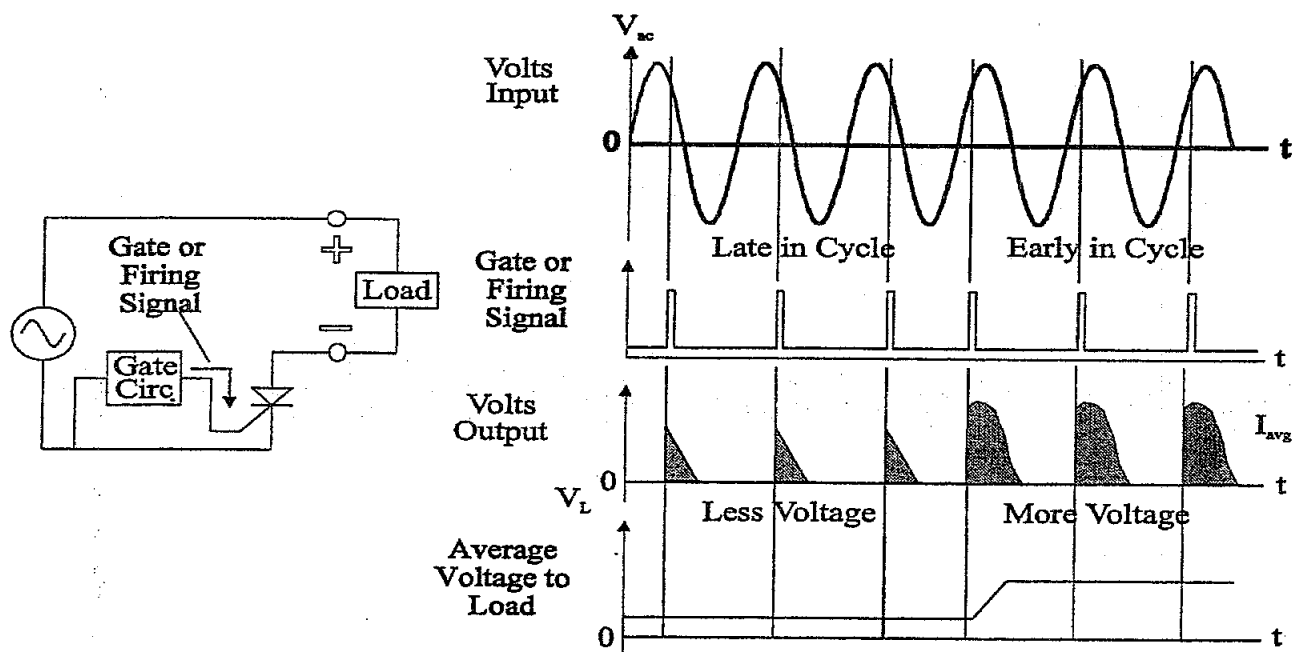


Figure 5.8: SCR Rectification

Silicon Controlled Rectifier Technology READ

The use of silicon controlled rectifier (SCR) technology for power control emerged in the 1970's and was widely used through the 1980's and into the 90's. Feedback circuits are added to send a signal to a printed circuit board. The control board then uses this information to adjust the firing circuit in order to provide control of the desired output current (or voltage) and V-I characteristic (**Figure 5.9**).

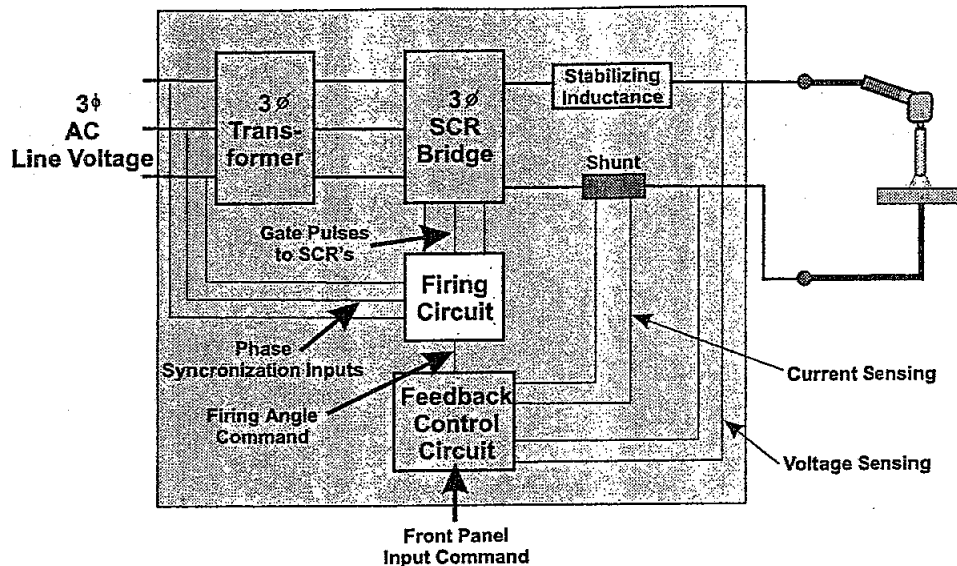


Figure 5.9:

Silicon Controlled Rectifier Technology

SCR controls have the advantage of being very energy efficient because the diodes are either on or off (conducting or not conducting) - operating like a switch. The amount of time they are on relative to the time they are off, controls the power that is passed, on average. A disadvantage of SCR Control is the very choppy output waveform, with times during the cycle when no voltage is output. For this reason, such control is most suitable with three-phase power sources where ripple frequency is higher and cycles shorter. This rippled output is usually compensated for with banks of capacitors (Figure 5.10). A capacitor stores energy and then outputs when voltage drops - essentially helping to fill in when voltage output would be zero.

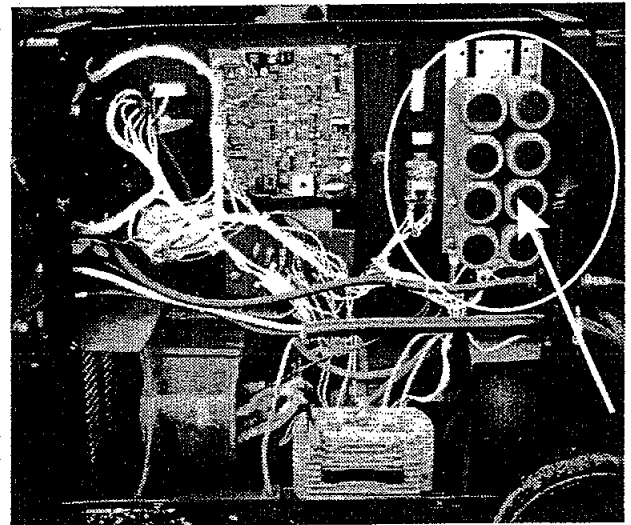
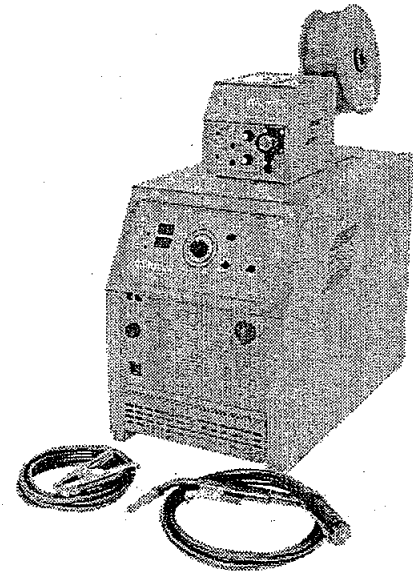


Figure 5.10: Capacitor Bank
(Courtesy of Hawkes Electric Arc)

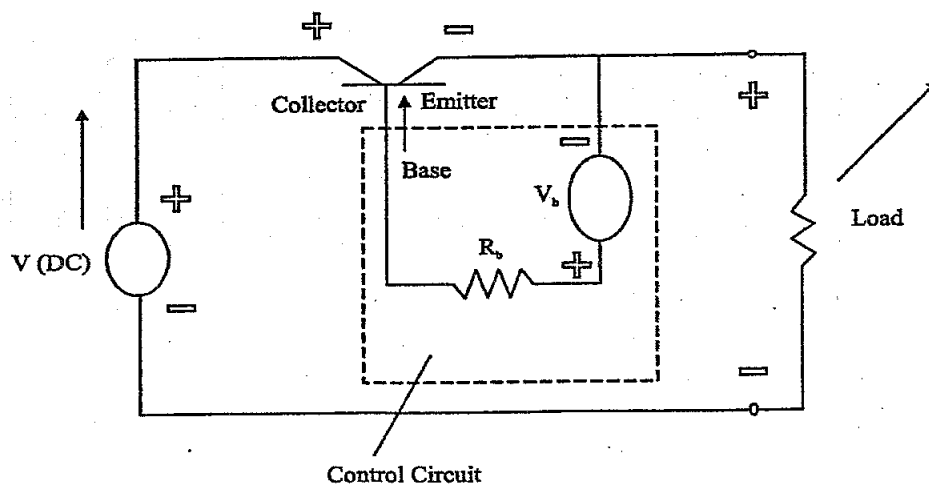
A related disadvantage is that control can only be applied from one cycle to the next. Once fired an SCR cannot be turned off. The flow of current will continue until conduction in the SCR stops naturally at the end of the AC half cycle. Control adjustments can be made by an electronic feedback system every 120th second for single-phase or every 360th of a second for three-phase. This may seem fast, but is relatively slow on the time scale of occurrences in the welding arc, especially when considering shorting-circuiting and other metal transfer mechanisms. **Figure 5.11** shows a thyristor-based welder with constant voltage DC output for GMAW, FCAW, and SAW up to 450 amps at 100% duty cycle or 550 amps at 60% duty cycle.

Figure 5.11: Thyristor-Based CV DC Welder for GMAW, FCAW, and SAW
(Photo courtesy of ESAB Welding and Cutting Products)



Transistor Circuits

Transistors are solid-state devices that control the flow of electrical current via a control terminal input (**Figure 5.12**). A so-called *base circuit* passes a small current between the base and emitter of the transistor. Given that a sufficient voltage is applied from a source between the collector and emitter of the transistor, the current passed by the transistor is proportional to the base current. The proportionality factor, β , is the *current gain* of the transistor, and is typically much greater than one. A



small current in the base circuit can control a large current in the collector to emitter circuit which provides the primary path for welding current or output. The transistor is much like a proportional valve for the control of current in a circuit.

Figure 5.12: Transistor Circuits

In the most basic application of a transistor, the transistor is placed in series between an electrical source and an electrical load as shown in **Figure 5.12**. When the current is less than the maximum, there is a surplus voltage drop across the transistor, and the transistor temperature rises as it dissipates the excess heat associated with the excess voltage times circuit current. In this *linear* mode of operation, the transistor is not very energy efficient except at maximum or minimum current, but is very useful for DC power control applications.

Transistor Controlled Machines

Transistors emerged as a practical method of controlling the output of welding machines in the 1970's, in parallel with the emergence of SCR controlled machines, and with some similarities in technology. The main idea is to put transistors in series with the DC output side of the power supply, downstream from conventional rectifiers (**Figure 5.13**).

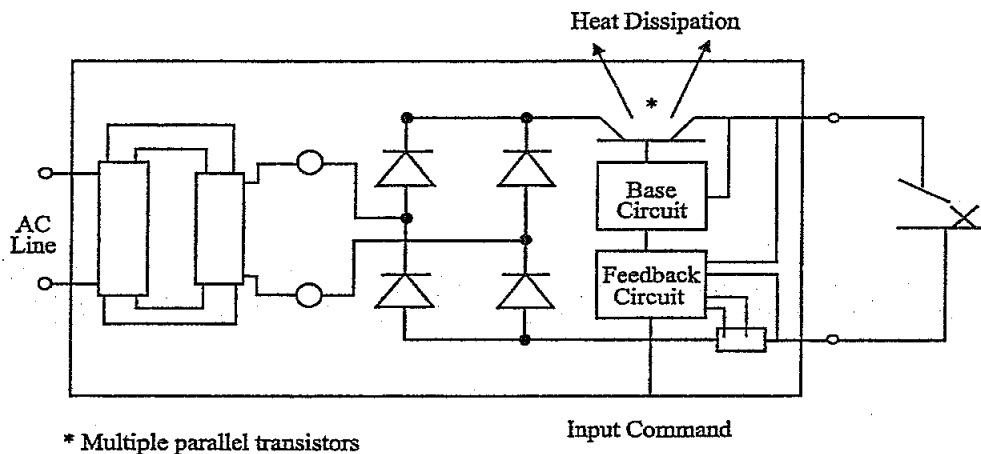


Figure 5.13: Transistor Controlled Machines

So-called *linear* type designs utilize the transistors as electronically variable resistance. Essentially, the greater the base terminal control current, the less the resistance of the transistor in the circuit. This produces an effect identical to the series or ballast resistance of early welding machines, with the same inefficiency. Such designs require many transistors operating in parallel, with water cooling, to provide reliable operation at the large currents used for welding. The advantage is that the current through the transistors can be precisely and rapidly controlled with a feedback circuit. Such machine designs are primarily limited to applications for lower current capacity, constant current machines for precision GTA welding applications.

Switching Circuits

The transistor can also be used in a "switching mode" to switch the voltage to a load on and off at a rapid rate. The current is switched between a maximum value and a low or zero value. Power loss due to resistive heating is minimized and the system becomes quite energy efficient. Power to the

load can be controlled by adjusting the amount of on time to off time. Two systems are used; frequency modulation and pulse width modulation.

Frequency modulation is where a fixed pulse width is used and the frequency varied to control the average on time. Pulse width modulation is where the frequency of pulsing is held fixed and the relative amount of on to off time is varied. Because a transistor can be switched at such a high speed, there is plenty of time to control output by either of the above methods. Switching is done at a much higher rate than line frequency (60Hz) to minimize the effect on the arc and maximize the speed that control can be accomplished with feedback. Switching frequencies of this type of machine are typically 1000's of hertz, to over 10,000 hertz although some pulse width modulation systems operate much above the audible range. An annoyance with some machines is the audible sound they emit at the switching frequency when operating the arc (the arc converts some energy into sound waves).

The *switching regulator*, designs were not widely used, but can be considered to be fore runners to modern inverter type welding machine circuits which are dominating current power source technology.

Inverter Technology

Inversion is the opposite of rectification. Inversion converts direct current into alternating current. Inverter is the electronic component which carries out this operation (**Figure 5.14**). Welding power source designs have rapidly evolved towards inverter technology in the recent years. Inverters utilize a switching type of regulation, mostly utilizing transistor type devices. The key difference with inverters is that switching is done on the high voltage primary side of the welding transformer, rather than on the more conventional secondary side. This has several advantages. One advantage is that currents are lower on the primary side, and thus less heat dissipation occurs in the transistors. This is at the expense of switching higher voltages (peak of the AC primary levels), compared to lower voltages on the secondary side, a disadvantage of the system. Since switching must operate on DC voltage, this requires that rectification be applied directly to the incoming AC prior to switching. The rectifier, placed in the primary side of the transformer therefore sees the transient voltage spikes which regularly occur in the supply power. Blown rectifiers were a common problem in early designs, especially in Canada where primary voltage is 600vrms. The technology of modern solid-state switching transistors has steadily advanced in the providing of the required reliability and some manufacturers have opted to include protection devices called MOV's to shunt the voltage spike around the rectifier.

The overwhelming advantage is that transformation to welding voltage is accomplished with a transformer operating at the high switching frequency (10,000's of hertz), rather than the low line frequency (60 Hz). Transformers designed for higher frequencies require much less iron core and windings than those designed for low frequency. The result is a many fold savings in weight and size of the step-down transformer. Inverter designs can thus be very small and efficient. This is at the expense of considerably more sophistication and complexity of electronic design. This is readily seen from the amount of circuitry inside an inverter as compared to conventional power source designs. However, the advantages well outweigh the disadvantages; and inverter designs are beginning to be predominant.

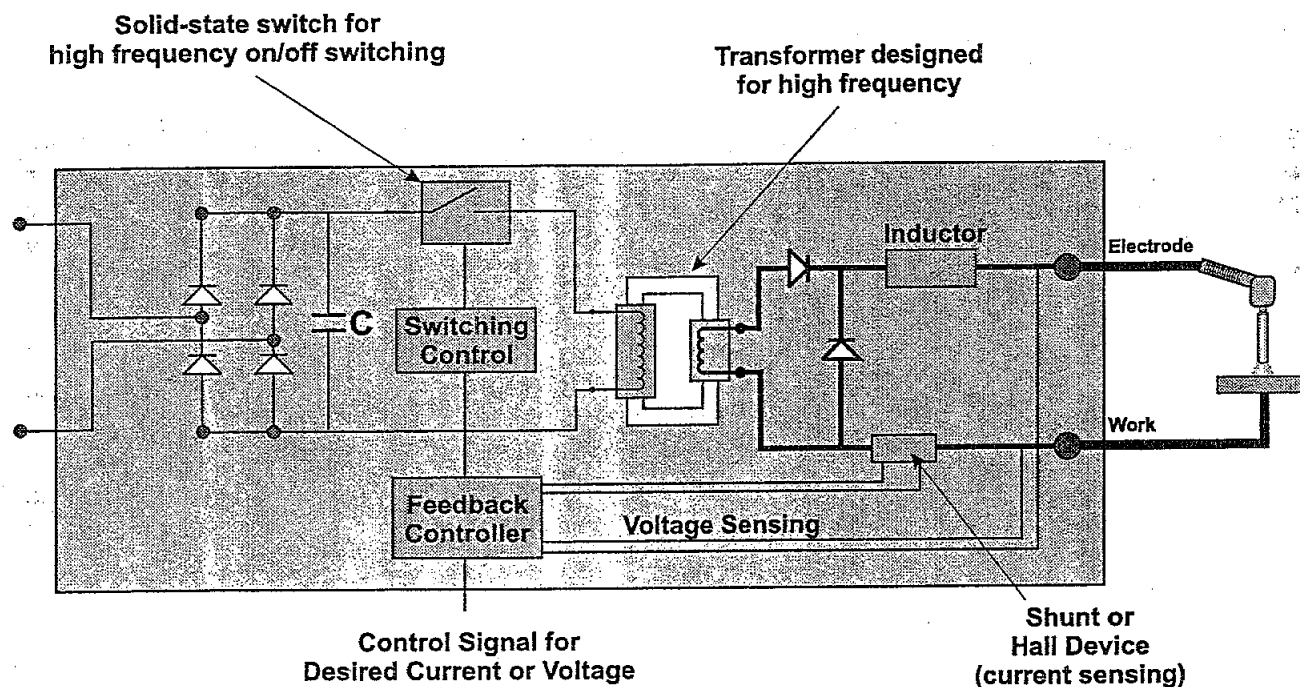


Figure 5.14: Inverter Technology

Figure 5.15 shows an inverter-based welder which can operate in both CC and CV modes, and can be used for GMAW, pulsed GMAW, SMAW, GTAW, pulsed GTAW, and FCAW with a rated output of 450 amps at 100% duty cycle and 565 amps at 60% duty cycle.

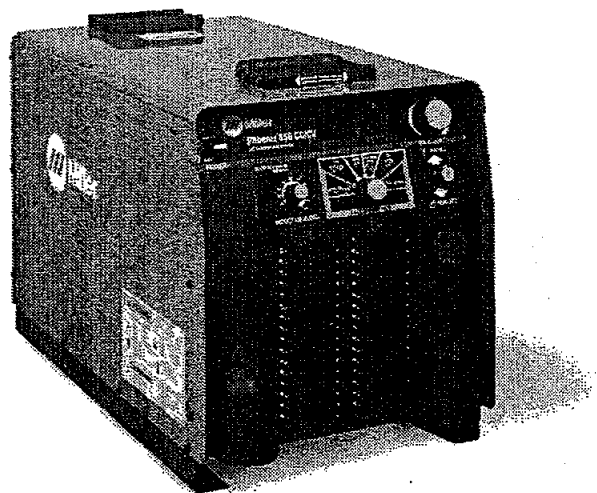


Figure 5.15: Inverter-Based CV/CC Welder
(Photo courtesy of Miller Electric Manufacturing Company)

Inverter Control Methods

Either pulse or frequency modulation is used to control the amount of power that is passed. In either case, the rectified line voltage is switched on and off by a solid-state switching device. Switching frequencies are typically 10,000's of hertz. The control of the amount of power is accomplished by either varying the pulse on time or the frequency of fixed pulses (**Figure 5.16**).

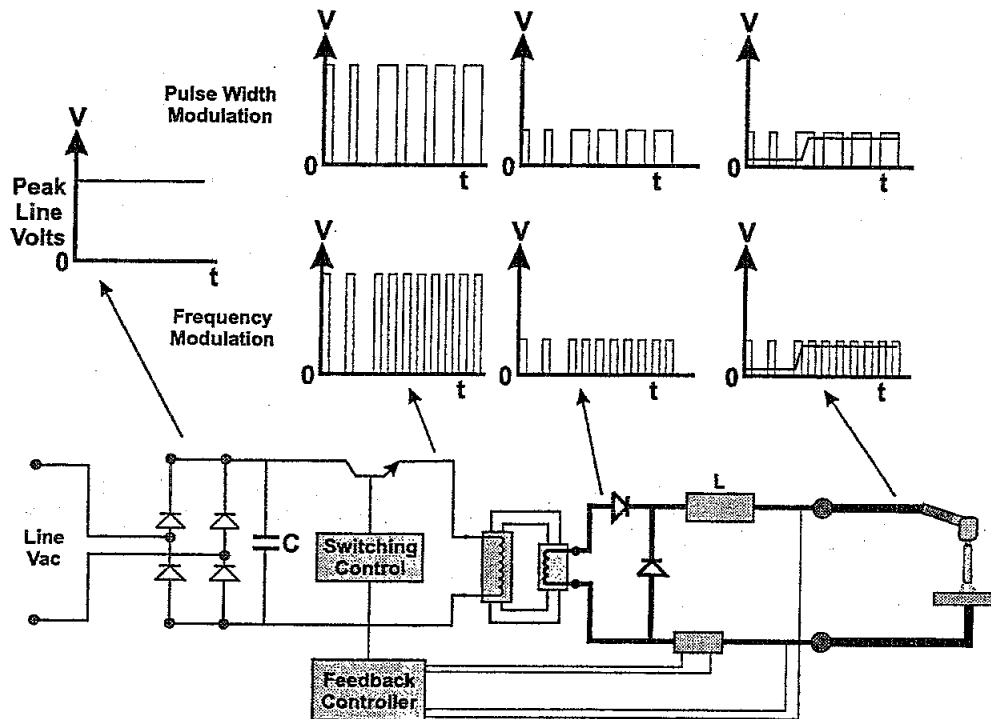


Figure 5.16: Inverter Control Methods

Control can be exhibited on a time scale of the switching frequency, which is fractions of milliseconds. The switching technologies thus provide machines with the fastest time response.

Section 6: Power Source Control Systems

Manual vs. Automatically Controlled Arcs

Classically, arcs are considered to be operated between fixed, non-consumable electrodes. With practical welding arcs, however, length varies either because the welding electrode is manually held, or because the electrode is melting off, or both. Control of the length of the arc is thus a significant consideration for arc welding systems.

In manual welding, the welder manually manipulates feed of the electrode to control the length of the arc. The most common examples are SMAW and GTAW. In each case the welder observes the arc, mainly its length, and manipulates the electrode in such a way as to keep the arc length constant. The welder must maintain the arc length within tight limits for the GTAW process, but the electrode is not consumed. In the SMAW process melting of the electrode by the arc causes the arc length to tend to increase. Feed of the electrode must be provided at a rate equal to its melt-off rate. This is accomplished by observation of the arc length. If the length is too long the electrode must be brought closer to the work, and visa versa.

The electrode can also be fed into the arc with a motorized system. With suitable power source characteristics and control circuits, the arc length can be automatically controlled. This leads to either semi-automatic or fully automatic welding systems. With semi-automatic systems, the welder still holds the weld torch, but the electrode is fed automatically through the torch. Fully automated systems control movement of the weld torch by the machine. Processes of this type are GMAW, FCAW, and SAW.

Power Source Droop

In the early days of arc welding, it was found that continuous, stable arcs could be maintained when source circuits had sufficient *internal series resistance*. Resistance in a source circuit tends to reduce the voltage delivered by the circuit as current flow increases. This can be expressed diagrammatically as a voltage source, with a resistance in series with the output terminals. Such a power source has a V-I characteristic which drops from the source voltage at zero current (the open circuit voltage), at a rate which is proportional to the resistance as current increases (Figure 6.1).

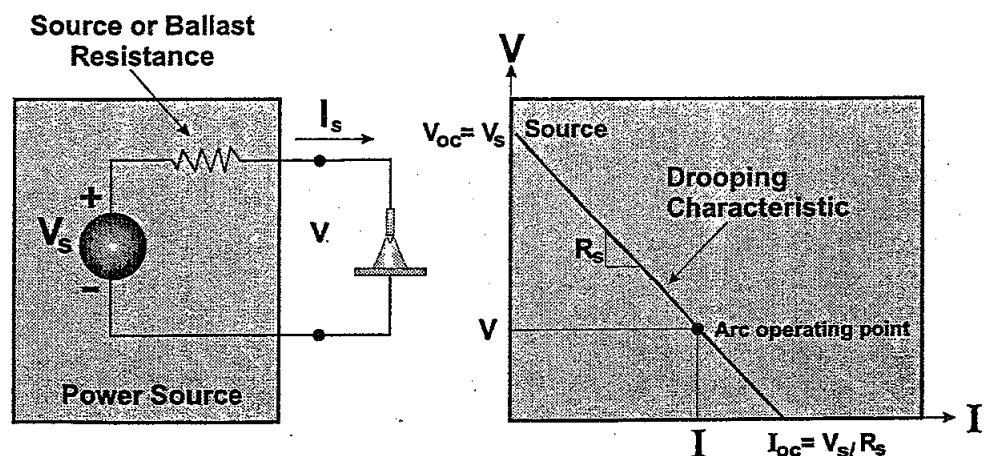


Figure 6.1: Power Source Droop

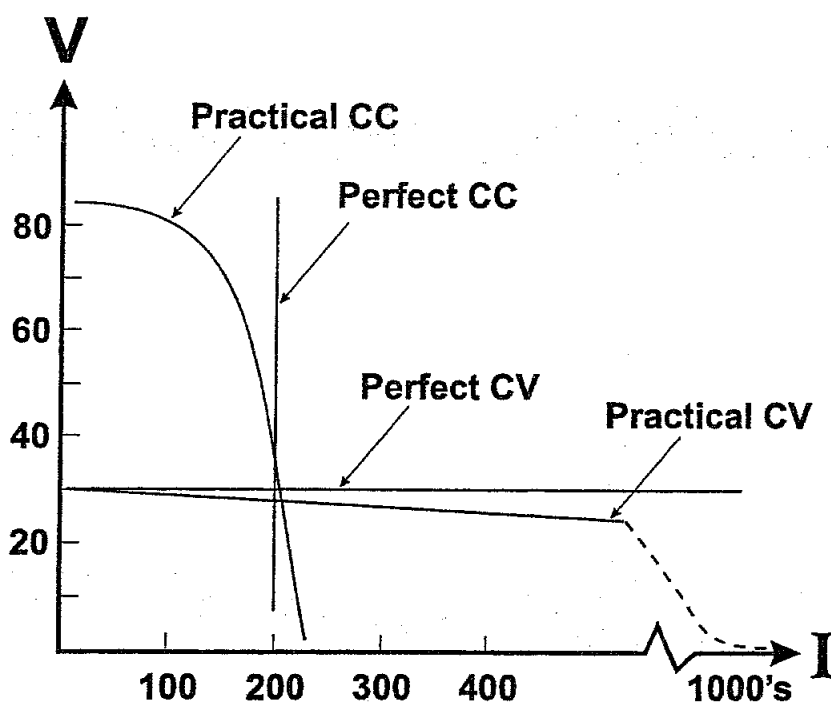
Such a power source circuit is sometimes said to have “droop”. When a resistance is added to a circuit to produce a drooping characteristic, it is sometimes called *ballast* resistance. (The ballast in a fluorescent lighting system serves the same purpose in stabilizing the operation of the gaseous electrical conduction process in the fluorescent tube.)

Constant Voltage/Constant Current

The most basic classification of welding power sources distinguishes them as **constant voltage (CV)** or **constant current (CC)** types. This classification corresponds to the type of V-I characteristic which the power source exhibits; how the voltage they deliver varies with the current supplied (Figure 6.2).

Constant voltage sources hold the output voltage relatively constant as current draw increases. An ideal CV source holds the voltage absolutely constant. With real CV sources the voltage drops slightly as current draw increases. For welding sources this is usually no more than a volt or so per 100 amperes of output current draw. The V-I characteristic of a CV source is very close to a horizontal straight line in a graphical representation. Most sources of electricity are inherently constant voltage. This includes utility power systems, common DC and AC electrical generators, batteries, and sources that convert AC line voltage to DC voltage for all kinds of electrical and electronic applications.

Figure 6.2: Constant Voltage/Constant Current



Constant current (CC) electrical sources exhibit a significant drop in output voltage as current draw increases. An ideal CC source provides an absolutely constant current output, with the output voltage varying according to the load. Real CC sources generally

produce some current variation. The V-I characteristic of a CC source tends to be nearly vertical in a graphical representation. Constant current sources are sometimes said to have “droop” or to be “droopers”. Another term for a constant current source is “variable voltage” or VV types because their output voltage varies. Welding source droop is typically greater than 10's of volts per hundred amperes of current.

CV versus CC Arc Operation

The static V-I characteristic of a welding power source is important to the maintenance of a stable welding arc. The power source arc characteristics are shown in **Figure 6.3**. Constant output voltage sources are represented by a horizontal line on a graphical V-I characteristic. The arc characteristic also tends toward a horizontal line, the operating point is not well defined. This is particularly the case when considering that the arc length may vary causing the arc characteristic to shift up and down - or the output voltage of the power source may fluctuate slightly. In practice this means that arc current will vary erratically, with minor variation in arc length, for manually held arcs. It is found to be impossible to "manually" maintain a stable, usable arc for welding with a constant voltage source.

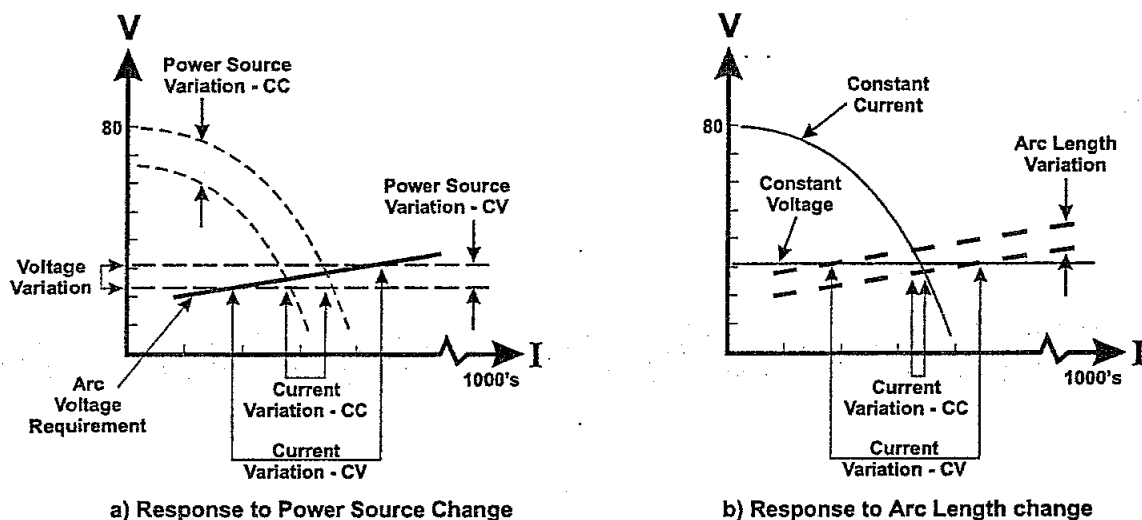


Figure 6.3: CV vs. CC Arc Operation

It can be seen that the addition of power source slope or droop, along with raising the voltage of the source (open-circuit voltage), better defines the operating point. The steeper the slope, the better the definition of the operating point, and the less the current will vary. An ideal CC source provides the most stable operating point in this regard. Constant current sources are found to be necessary for operation of manual arcs. However, certain applications of manual welding require current variation to accompany voltage change due to arc manipulation, in particular, when performing the root pass in a pipe joint. (See Module 4)

Manual Arc Control

In SMAW, the welder controls the arc length by manipulating the electrode feed rate. The welder observes the arc and feeds the electrode faster to shorten the arc, and slower to lengthen the arc. The welder's main objective is to maintain an optimum arc length. The optimum arc is usually as short as possible to concentrate the heat, without short-circuiting and erratic metal transfer.

The burn-off rate of the electrode is proportional to the arc current. Thus, with a constant current power source for manual welding, the electrode burn-off rate is fixed by the current setting. The welder controls the arc length via the feed rate of the electrode. To make the arc shorter, the welder feeds the electrode faster, such that feed rate exceeds the burn-off rate. To make the arc longer, the welder slows the electrode feed rate, such that it is less than the burn-off rate. Hand-and-eye coordination allows the arc length to be continuously maintained or adjusted by this process.

Manual Arc Control Inputs

To control the amount of welding heat, the primary welder control input is the welding current, which is set at the power source (Figure 6.4). For GTAW, a foot pedal is often provided to allow the welder to directly adjust the current while welding. Foot pedal controls are not found to be practical for SMAW which requires the arc be stopped for current adjustment at the machine.

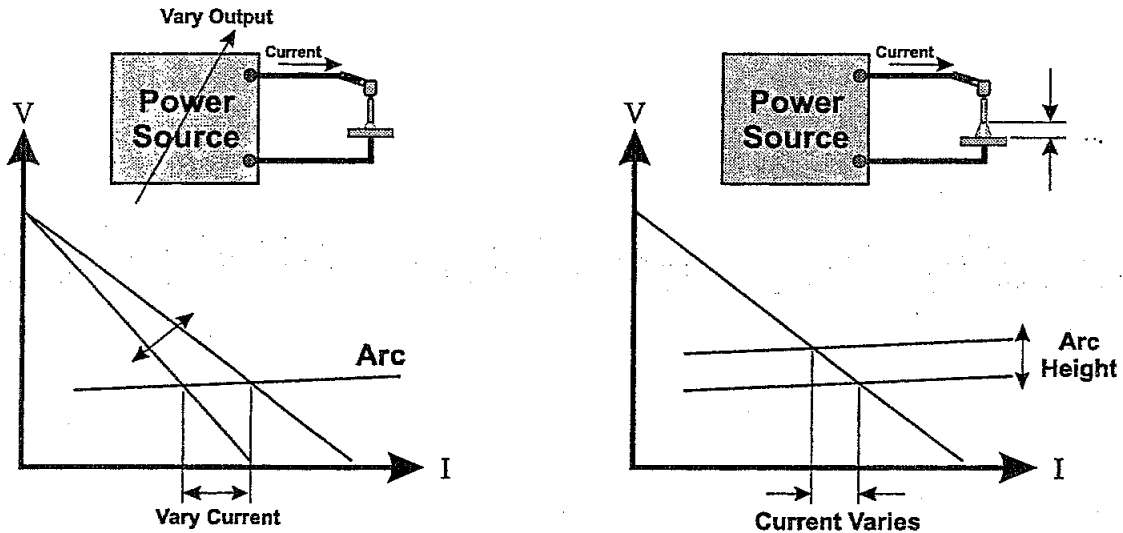


Figure 6.4: Manual Arc Control Inputs

The welder can exhibit indirect control over the weld current by manipulating the arc length, dependent on the power source characteristic. Manipulation of current is useful for allowing fine adjustment to heat input and electrode melt-off rate. The amount of control which is possible depends on the amount of droop in the CC power source characteristic. If the droop is shallow, significant current change can be achieved via arc length. Increasing the arc length will require higher arc voltage and the current will drop, and visa versa. If the droop is steep, approaching an ideal CC characteristic, little or no change in current can be achieved. Welders, thus, may prefer some droop so that they have an instantaneous means of controlling current and heat input. However, it takes more skill to control the arc since less droop (more CV-like) promotes current fluctuation and an unsteady arc.

Self-Regulation of the Arc

When the control of electrode feed is automated, it is possible to maintain an arc with a constant voltage type of power source (Figure 6.5).

It is a relatively recent discovery in the history of welding arcs that a stable arc can be maintained with a constant voltage power source if the electrode is fed at a suitable constant speed (mechanically fed). The electrode feed speed demands a current which is of the proper amount to melt off the electrode at an equal rate. If the current is not sufficient, the electrode will not melt-off fast enough and the arc length will decrease, or visa versa. This leads to regulation of the arc length as follows. If the arc is too long, the CV power source will deliver less current than required to melt off the wire at the required rate. This will cause the arc length to decrease with time, and the arc current to increase. Arc length will decrease until the current rises to provide a melt-off rate to match the feed rate. The opposite will occur if the arc length is too short. The arc length will thus regulate around the operating point where the current provides the required melt-off rate. It is found that a welding arc in such a manner is stable and usable for welding. The arc is said to self-regulate.

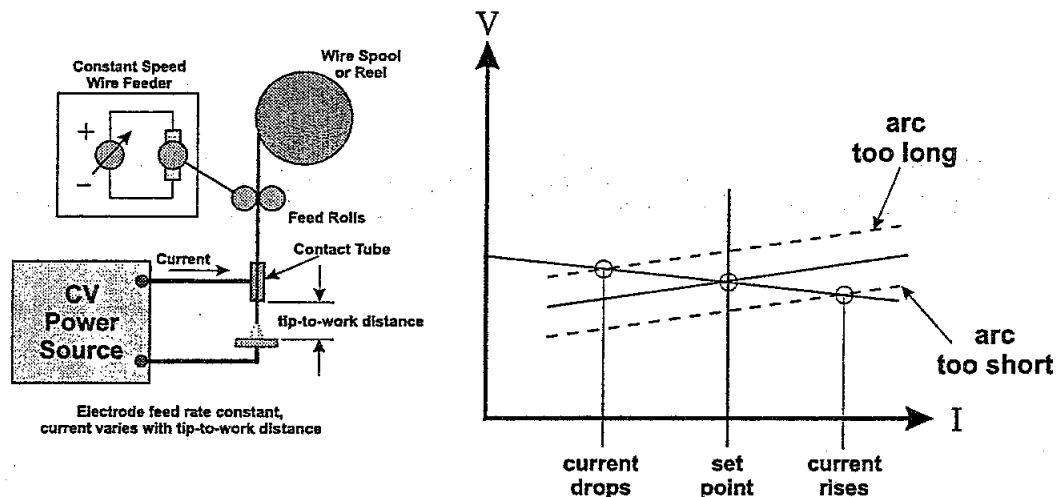


Figure 6.5: Self Regulation of the Arc

Most systems with automated wire feed, such as GMAW, FCAW, etc., use this phenomenon of self-regulation of the arc; employing constant voltage power sources with constant speed electrode (wire) feeders.

CV System Control Inputs

The power source voltage and wire feed rate are the primary operator inputs with CV self-regulating systems.

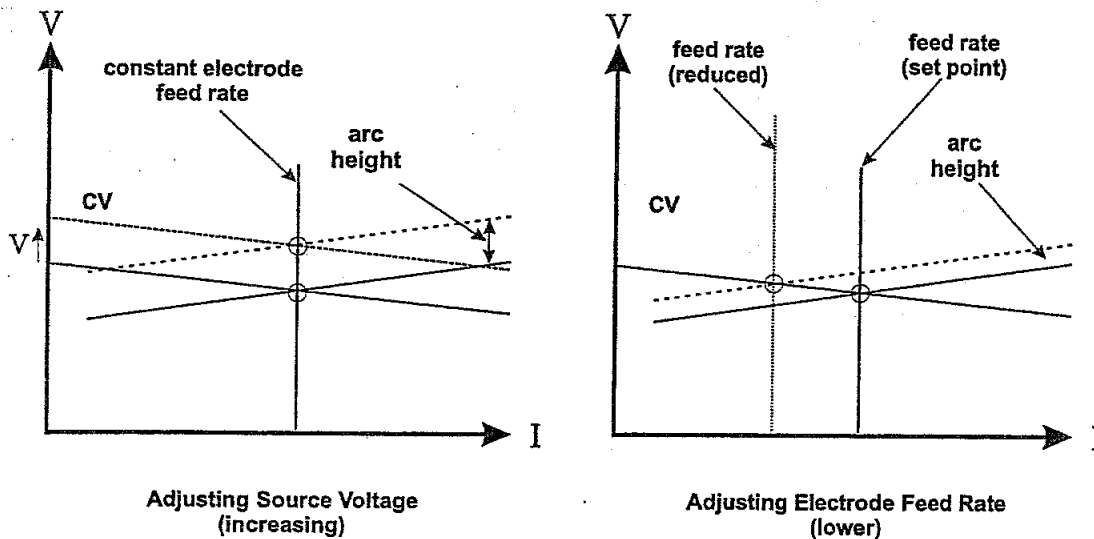


Figure 6.6: CV Control System Inputs

Power source voltage, as represented on the V-I graphic as a raising and lowering of the power source characteristic, mainly determines arc length (Figure 6.6).

Electrode feed rate primarily determines arc current. It can be seen on the V-I graphic that it will also affect arc length due to the slope of the arc characteristic. Increasing electrode feed rate tends to decrease arc length, and decreasing electrode feed rate tends to increase arc length. The result is that adjustments to electrode feed rate, such as to adjust heat input or metal deposition rate, must be coupled with voltage adjustments to maintain the optimum arc length. An optimum arc length is short enough for good heat concentration, but not so short as to be subject to short-circuiting and erratic metal transfer.

Voltage Controlled Wire Feed

The other basic method of automatic regulation of the arc can be accomplished with a constant current type power source, and a variable speed electrode feed system (Figure 6.7). In this case, the variable arc voltage (provided by the constant current power source) is used to generate a signal to control the electrode feed rate. With this system the electrode melt-off rate is fixed by the power source current. If the wire feed rate is not fast enough to match the melt-off rate, then the arc will get longer, the arc voltage will rise, and the wire feed rate will increase. This will go on until the arc is long enough to feed the wire and a sufficient speed for the current setting. The opposite will occur if the wire feed speed is too fast for the set current - the arc will get shorter to slow the wire speed down.

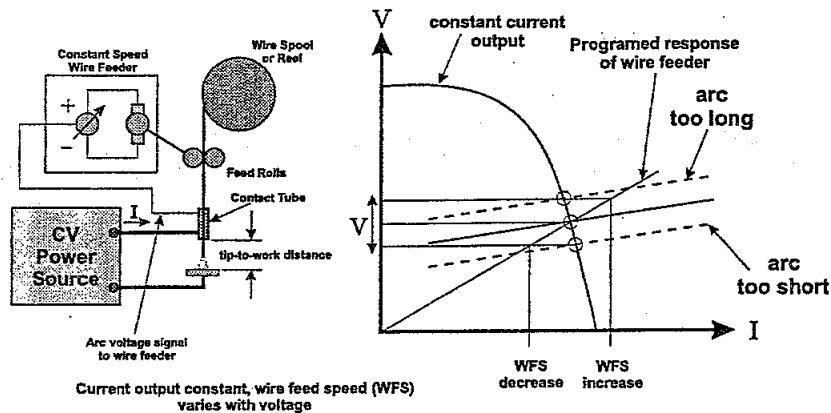


Figure 6.7: Voltage Controlled Wire Feed

Also, the arc will also tend to regulate at a length determined between the balance of current and electrode feed rate. If the arc gets too long, the arc voltage will increase and the feeder will drive the electrode faster than it is melting off. This response tends to decrease the arc length. The length will decrease until the voltage drops to where electrode is being fed at a rate equal to its fixed melt-off rate. If the arc is too short, the opposite will occur. Thus the arc length will regulate about an operating point where the electrode feed rate equals the fixed melt-off rate. This method of automatic arc length control gives a stable and usable arc for welding. Such systems are called voltage controlled wire feed systems. Voltage controlled wire feed actually predates the discovery of self-regulation. Self-regulation systems have prevailed because of their greater simplicity (constant voltage sources and no control interconnections between the power source and wire feeder). There are some modern systems for GMA welding which use the voltage controlled wire feed system, but it is not in wide use.

Voltage Controlled Inputs

With voltage controlled systems the operator inputs are welding current, and a control which dictates the amount of electrode feed rate for a given arc voltage. The latter is via a characteristic of the circuit coupling the electrode feeder with the power source (Figure 6.8).

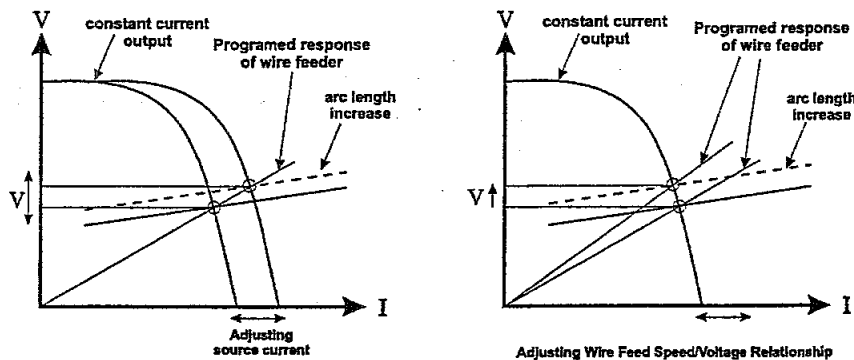


Figure 6.8: Voltage Controlled Inputs

The electrode feed rate/voltage relationship controls arc length. The current mainly controls the electrode feed rate.

Typically, the current setting on the power source is used to increase or decrease electrode feed rate, and hence, heat input and metal deposition. This tends to change the arc length, since more current requires more voltage to feed electrode at a higher rate. The result is an increased arc length with increased current, or visa versa. The electrode feed rate/voltage must be adjusted to compensate and restore the arc to its desired length.

Synergic Welding Control

The technology of synergic welding control is based on the emergence of imbedded computer- based technologies in welding equipment (**Figure 6.9**). In its simplest form, synergic control is the term used to describe a system in which the welding power source and wire feeder are more intimately integrated than is typical with conventional systems (e.g., simple CV self-regulating arc systems with a separately controlled power source and wire feeder). For instance, a synergic system might be designed to sense the wire feed rate and automatically adjust the power source voltage to keep the arc at an optimum length. This makes the process easier to operate and more trouble-free. A similar scenario could be applied to a voltage controlled wire feed system. Completely new control schemes are also possible.

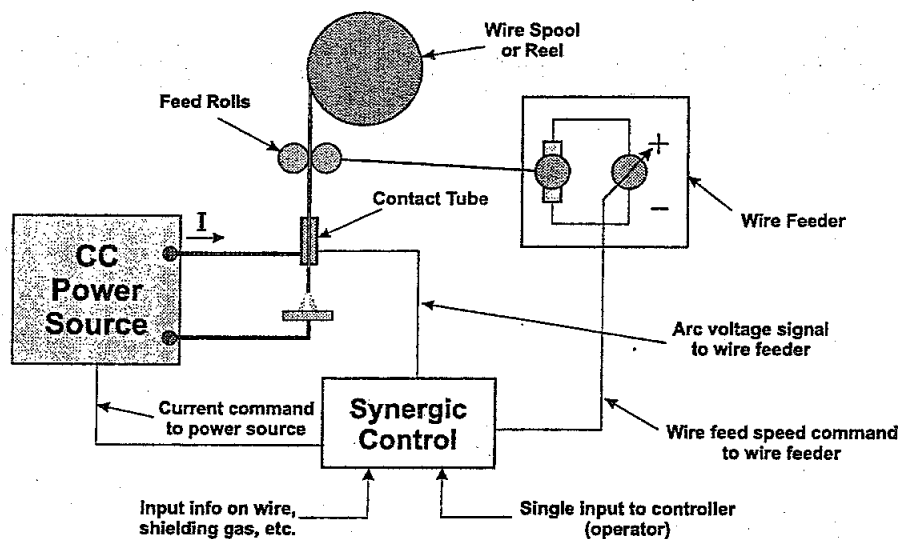


Figure 6.9: Synergic Welding Control

In order to accomplish this, computational capability is required, as in the form of microprocessor based systems. Also, basic data is required as to how a particular arc process operates under various conditions. For instance, how much does the voltage have to be adjusted to compensate for a certain amount of wire speed change? This is not a trivial undertaking relative to the large variety of welding process conditions. The so-called synergic relationships typically take the form of schedules for various wire and shielding gas characteristics that must be selected for synergic operation.

Open Circuit Voltage *KNOW THIS.*

The open-circuit voltage of a welding power source is an important electrical characteristic to its operation. The open-circuit voltage is the voltage the source delivers without an arc, that is with zero current being delivered. This is the voltage that exists at its output terminals when the power supply is on, but an arc is not established.

Constant current supplies tend to have high open-circuit voltages due to the nature of their V-I characteristic. Most regulations limit the maximum open circuit voltage of a CC power source to 80v, for safety reasons. Even ideal CC supplies are designed to supply only a limited output voltage as current decreases, giving them the unusual looking V-I characteristic as shown in **Figure 6.10**.

It is desirable to design a welding power source to have a high open-circuit voltage, since higher open-circuit voltage is required for arc initiation. CV supplies are designed to operate at a constant voltage equal to the arc voltage, thus do not inherently have high open-circuit voltages. Circuits to provide extra voltage under open-circuit conditions are sometimes included in CV power sources to help arc starting. They are sometimes called hot start circuits.

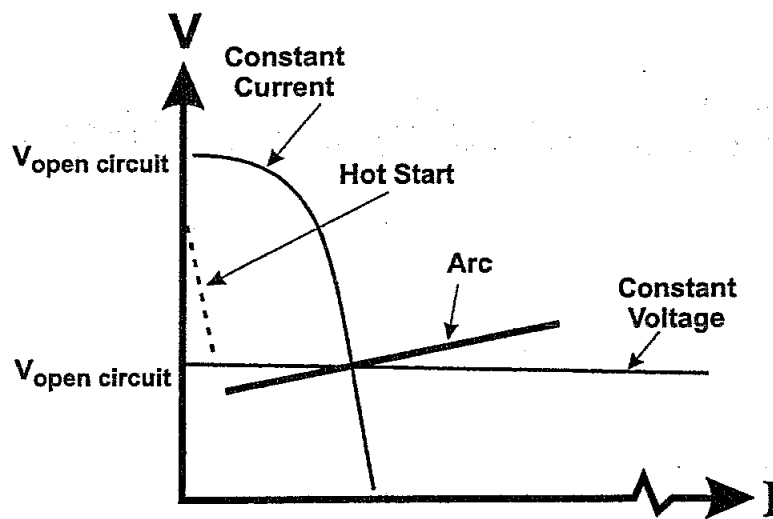


Figure 6.10: Open-Circuit Voltage

Short Circuit Current

Short-circuit current is the current that a power source delivers when its output is shorted (no arc). In arc welding this occurs during arc starting, or whenever metal bridges the gap during metal transfer with a consumable electrode. Constant current power sources have inherently low short-circuit current capability due to their droop (**Figure 6.11**). Constant voltage sources have inherently high short-circuit current capabilities since there are no circuit elements to limit the current.

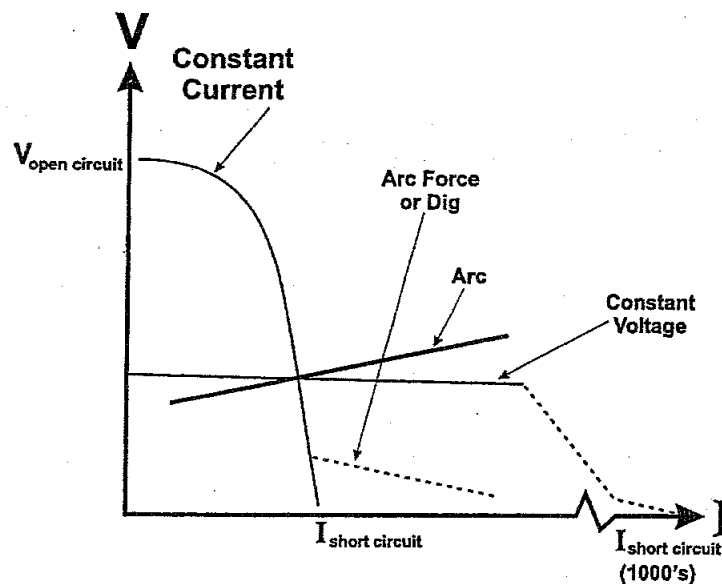


Figure 6.11: Short Circuit Current

Short-circuit current exhibits itself in the behavior of the arc process when shorting occurs. High short-circuit current tends to produce violent shorting reactions, ejecting metal in starts or metal transfer events, producing spatter. Low short-circuit current leads to sticking of the electrode and extinguishing of the arc. The latter results in difficulty in maintaining a manual arc with a CC power source. Constant current supplies usually include circuitry to provide a flaring of the V-I characteristic at low voltages (lower than typical arc voltages) to higher current. These are called "arc force or arc dig" circuits. The amount of short circuit current is often made adjustable via a knob on the panel of the welding machine so that a welder can adapt the short-circuit current to the particular electrode and welding application. This will be adjusted to prevent sticking or stubbing of the electrode, without excessive generation of spatter.

Short-circuit current is also a factor in CV welding machine designs. The problem tends to be excessive short-circuit current resulting in violent starting and erratic metal transfer. Constant voltage machines are thus designed with some droop, to limit short-circuit current capacity. Inductance or its equivalent is also added to the circuit and is effective at limiting the rate of current rise during momentary shorting. (See Module 4)

Reactive Current Control

The output current of manual machines must be controlled to produce a drooping or CC characteristic. The control method must allow for adjustment of the current. A significant development in power sources was the use of inductance to control current. In this regard, AC circuits provide the advantage that slope can be provided by the use of inductance. In welding circuits this is often called *reactance* or the inductive reactance of the inductor, and the inductor is called a *reactor*. Older machines are thus found that are *reactance* or *reactor controlled* welding machines (Figure 6.12). In effect, the series reactor (inductance) causes a drop in the AC load voltage as current increases, just like a

resistor causes a drop in DC voltage (or AC for that matter). The reactor must be placed before the rectifiers in a DC source since it is an AC device. Some means of adjustment of the reactance is provided for a means of adjusting the current output by varying the amount of output droop or slope. More reactance provides more droop and less current. Less reactance provides less droop and more current.

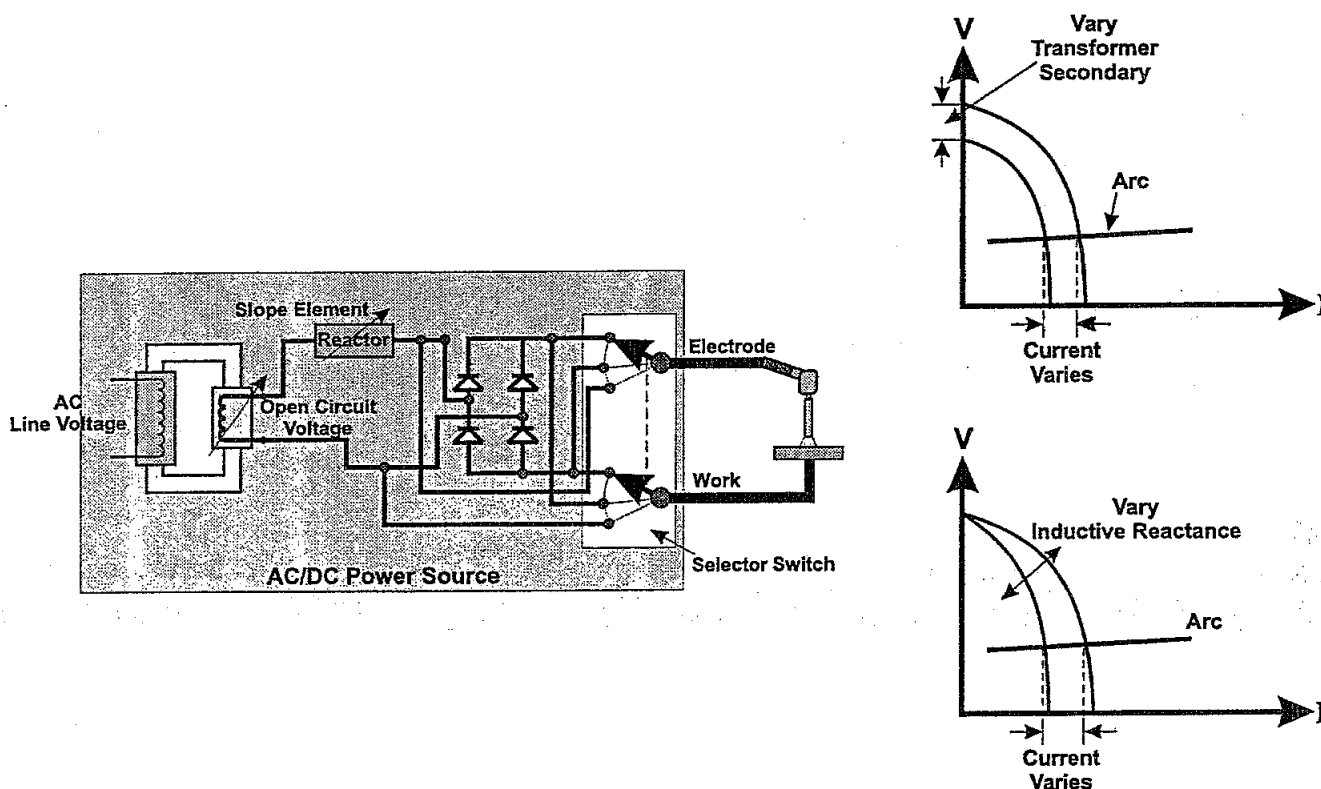


Figure 6.12: Reactive Current Control

Single-phase sources use a single reactor. Three-phase sources use three reactors, one for each phase.

Tap Controlled Reactance

A simple method for providing control of the output of welding machines with transformers and reactors is by tapping (Figure 6.13). In essence, connections are provided to the transformer secondary winding and reactor windings at multiple internal points. This allows the number of secondary or reactor windings to be varied, to vary the machine output. Tapping can be accomplished either with bolted terminal type connections, or with large switch mechanisms which engage with different tap points. Tapping is a rather crude way to provide control, and does not provide a continuous range of variation. In some cases, tapping is used for coarse range changing, and another control mechanism is used to provide a finer level of output control.

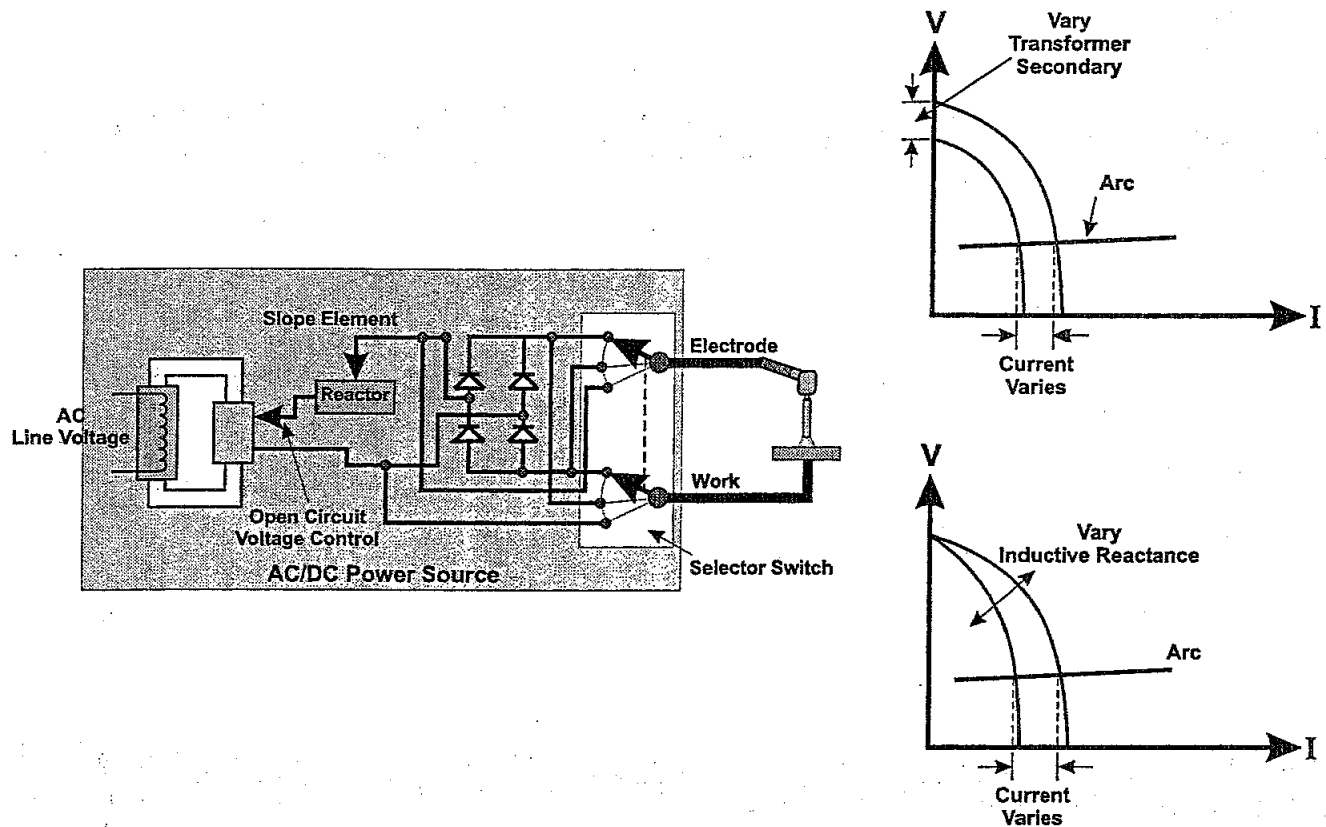


Figure 6.13: Tap Controlled Reactance

Magnetic Circuit Controlled Reactance

A very successful method of welding machine output control with reactors has been via the utilization of *magnetic circuit* methods. Magnetic circuits have to do with the flow of magnetic flux in the iron cores of transformers and reactors. Controlling of the flow of the flux allows control of the inductance (Figure 6.14).

A common magnetic circuit design was to use a variable reactor core geometry. For instance, a member of the iron core can be moved to produce a variable *air gap* in the magnetic circuit of the core. Less air gap gives less magnetic core reluctance and, hence, more magnetic field in the core and more inductive effect. More air gap accomplishes the opposite. Thus mechanical movement of the core element controls output slope and current. The simplest machines utilize a crank arrangement. More complex machines might use a motor driven mechanism. Such a control might be used in conjunction with taps for selecting ranges of output.

An advantage of this type of control is that it provides for smooth and infinite variation of current over the range of the machine.

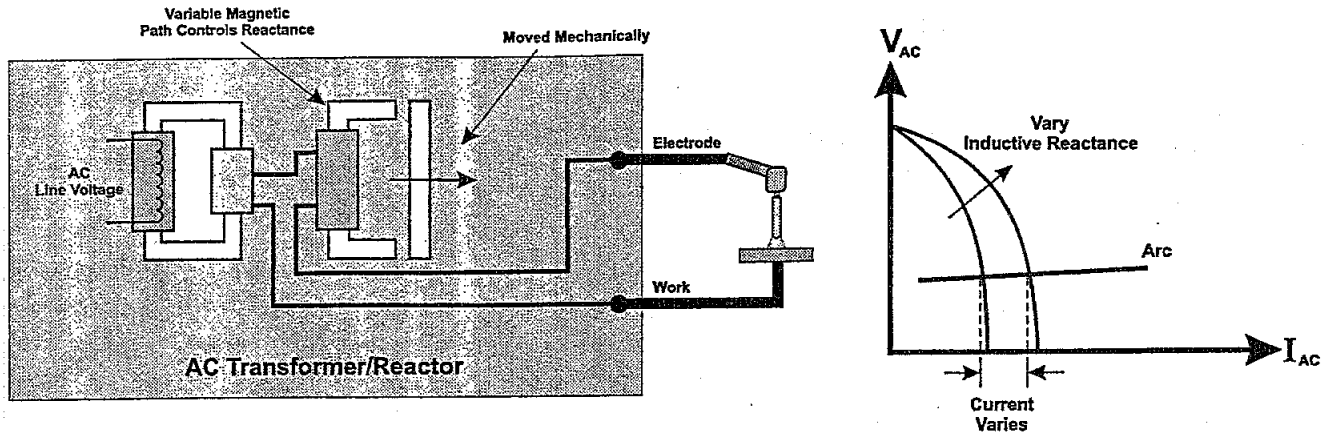


Figure 6.14: Magnetic Circuit Controlled Reactance

Magnetic Circuit Controlled Transformer

Another reactance approach utilizes only a transformer, which was popular because of its simplicity. In effect, an inefficient transformer design is utilized which involves provision for leakage flux, or magnetic flux from the primary which does not couple through the transformer core to the secondary. Such a transformer does not just reduce the voltage, but has an inductance equal to that of the primary windings through the leakage path. The inductance behaves as if it were in series with the transformer secondary. Either a movable iron core, or a movable coil element is utilized to allow variation of inductance and, hence, output slope for current control. This could be used in conjunction with taps for range selection (Figure 6.15).

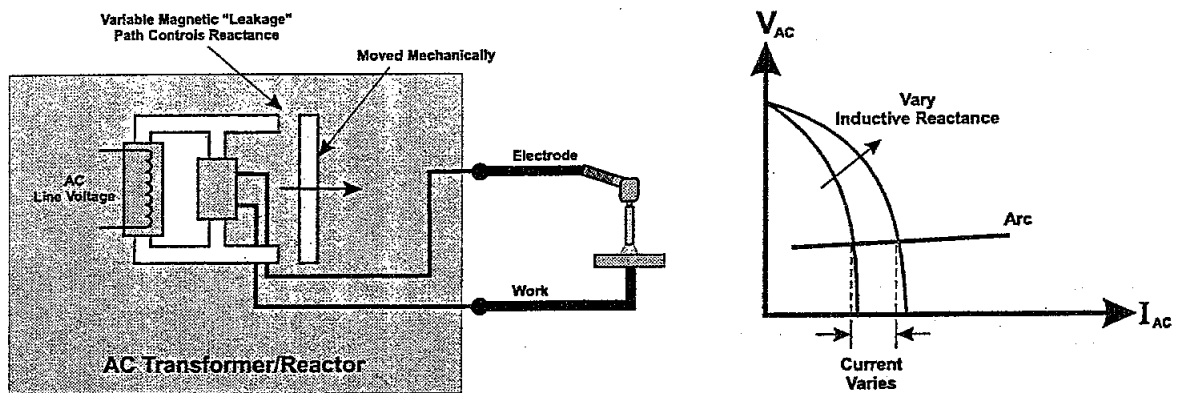


Figure 6.15: Magnetic Circuit Controlled Transformer

Transformers designed in this manner are sometimes called *loosely coupled* transformer designs, since all of the magnetic field of the primary is not coupled through the secondary. This is as opposed to *tightly coupled* transformer designs in which all flux is coupled from the primary to the secondary. The latter provide constant voltage output, as compared to the former which provide the drooping or more constant current type of output.

The loosely coupled transformer for drooping power source design was popular because of greater simplicity (less components) over the separate transformer and reactor approach. Designs often utilized a moving secondary coil rather than a moving iron core element. In this case, the coil was moved away from the primary to reduce coupling.

Saturable Reactors

A significant advance in reactor controlled machines was in the use of saturable reactors (Figure 6.16). The inductance of a saturable reactor is varied by saturation of the magnetic core of the reactor with a magnetic field from an auxiliary, low power control winding. Increasing control winding current increases core saturation which decreases the effective inductance from a maximum with no saturation (zero control coil current). Since control winding currents are DC, it was necessary to have two control windings on separate reactances (cores), one for the positive and one for the negative cycle of AC (not shown in illustration). The transformation effect of voltage from the welding to the control circuit was also canceled out in this way.

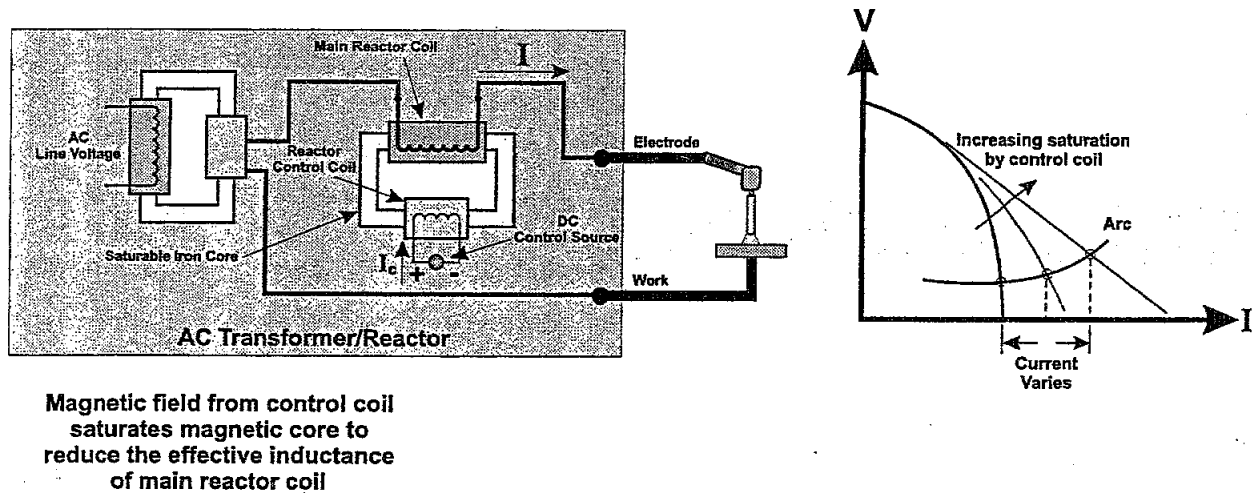


Figure 6.16: Saturable Reactors

Saturable reactors provided two key advances. First, inductance could be varied without moving parts. Second, electrical control of inductance allowed electrical feedback to be implemented to provide more precise control of electrical output. When used with feedback, saturable reactor controls are called *magnetic amplifiers*, or *mag-amps*. Amplification results from the ability to control large electrical current (high power) through the reactor with low electrical current (low power) through the control winding. This type of control was widely used in the 60's and 70's, especially for more precision applications like GTAW. It was also a popular way of controlling electrical power in any high power electrical circuits.

Saturation could also be employed with loosely coupled transformer designs. In this case saturation of the transformer core was controlled with a control winding. This varies the amount of coupling between the primary and secondary, and thus the amount of "leakage inductance".

Inductive Power Factor

A problem with reactively controlled welding machines is low power factor - as low as 0.5 or even less. The high inductance in the machines for slope control causes large phase shifts between primary current and voltage from the AC line. The machines thus draw excessive primary current for the actual electrical power utilized at the arc. Power factor correction capacitors were often installed across the input line connection on such machines to correct the power factor (Figure 6.17).

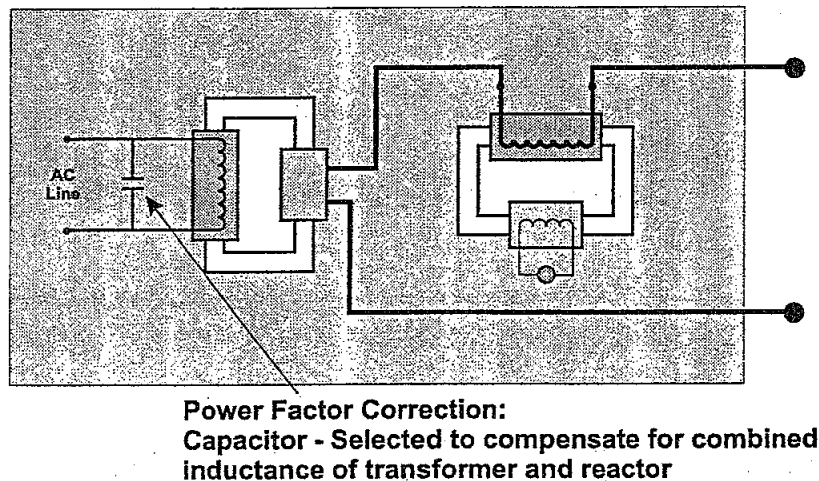


Figure 6.17: Inductive Power Factor

Electrical Feedback Control

Saturable reactors introduced the prospect for the control of the output of welding power sources by feedback control (Figure 6.18). Feedback is accomplished by electrically measuring the output quantity to be controlled (e.g., current for a manual welding machine). The measurement is compared electrically to a control input, usually a voltage generated from a potentiometer circuit via a knob on the front panel of the machine, which represents the desired current. A circuit is used to measure the sign and magnitude of the difference between the two to produce the so-called error signal between the actual and desired outputs. The error signal is input (feedback) to the control means (e.g., the saturable reactor control winding) to produce a correction to the output. Thus, if the current is higher than desired, the error is negative (desired minus actual value), and the input current to the saturable reactor control winding will be increased to increase the inductance and reduce the current. If the current is lower than desired, the opposite will occur to increase the current.

This is analogous to the cruise, or speed control in modern automobiles. Manual control of speed requires that the driver watch the speedometer and manipulate the accelerator to keep speed constant. The cruise control eliminates manual control and requires only that the driver input a desired speed.

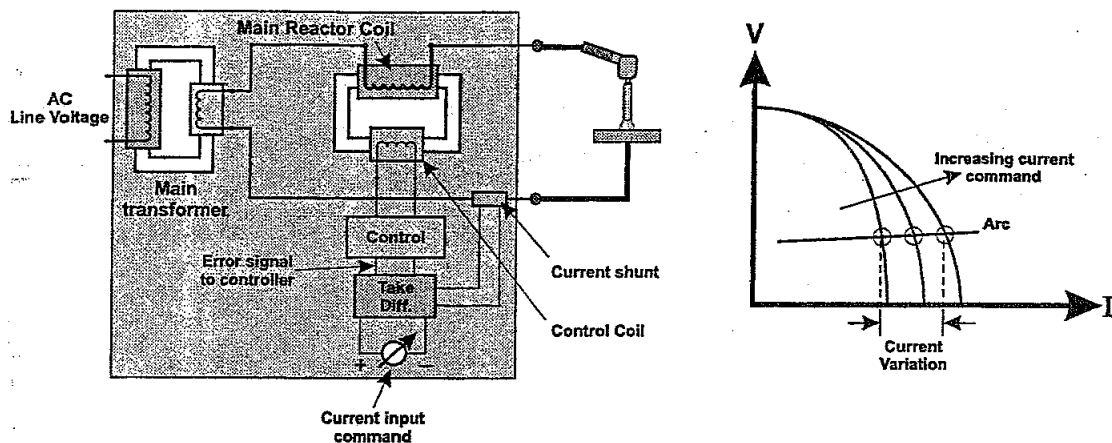


Figure 6.18: Electrical Feedback Control

Such feedback controls allow the implementation of power source V-I characteristics which approach that of ideal constant current (or ideal constant voltage if desired) characteristics.

Feedback control is always employed in the design of modern, industrial welding power sources. Solid-state devices are, however, used to provide the control means.

Output or Stabilizing Inductance

It is common to add inductance to the DC output side of a DC welding machine. This should be distinguished from the use of a reactor to control the output slope or droop of a constant current machine. Inductance on the DC output side is referred to as the stabilizing inductance, or just inductance (Figure 6.19). The stabilizing inductance provides several useful characteristics, all associated with the dynamic, as opposed to static, characteristic of the machine.

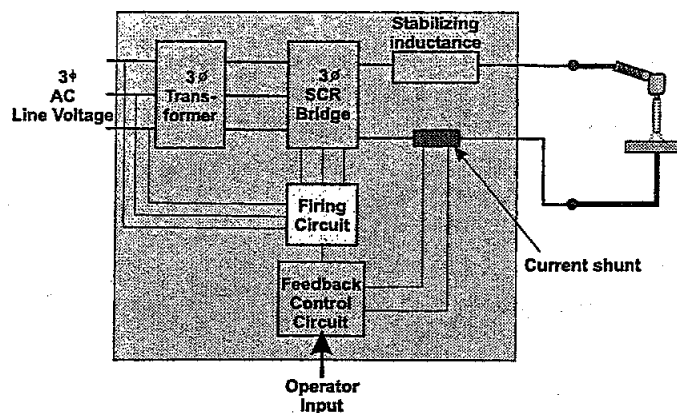


Figure 6.19: Output or Stabilizing Inductance

One characteristic of inductance is that it provides an inductive voltage surge when a short is broken. This helps in initiating or reinitiating of the arc. Reinitiation is important where shorting occurs frequently in metal transfer, and reinitiation of the arc must occur reliably for stable arc operation.

Another related characteristic of inductance is that it lowers the circuit voltage when current rises suddenly (e.g., due to a short) and transiently limits short-circuit current and violent explosion of the metal bridge. This makes metal transfer smoother and reduces weld spatter. This is important with the use of CV machines.

Finally, inductance produces filtering of the output current and voltage of the power source. This smoothes out ripple from the rectification process, and from the choppy result of SCR type control.

A disadvantage of inductance in the power source output is that it limits the rate that current can be made to rise and fall when circuits are used to pulse the welding current. Inductance may have desirable or undesirable affects in a welding circuit, just as mass has such affects in a mechanical system. For instance, flywheel mass in an engine makes the engine run smoother by opposing sudden changes in engine speed as cylinders fire. On the other hand, it also contributes to limiting the rate at which the speed of the engine can increase when accelerating. There is some compromise in the design of the flywheel for optimum performance. Such is the situation with inductance in a welding circuit.

Multi-Process Power Sources

Feedback controls employed in modern welding power source design provide the potential for great flexibility in their output characteristic. The output characteristic, for instance whether it is constant current, constant voltage, or something in between, is determined by the feedback control circuit design. This is independent of the actual power control element utilized (e.g., resistor, reactor, SCR). Thus a single machine can be designed with various control circuits, that can be selected by the user by switches on the front panel. A characteristic of a single machine can thus be selected so that it can be used in a constant current mode for SMAW or GTAW, or in a constant voltage mode such that it can be used for GMAW (Figure 6.20). Due to the rapidity of control with inverters, the dynamics of the machine can also be tailored by the control circuit characteristic. This has allowed the design of machines with the capability for multi-process operation. This is a new development in the industry, since in the past welding machines have been designed and marketed for application to a single process (e.g., SMAW, GTAW or GMAW) and were strictly classified as CC or CV machines.

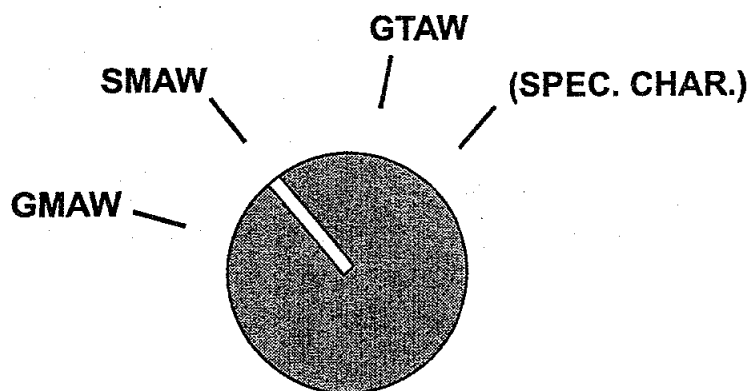


Figure 6.20: Multi-Process Power Sources

Microprocessor Controls

Circuitry used for welding power source control has grown in sophistication with the available technologies. Early controls utilized discrete electrical and electronic components such as resistors, switches, relays, motors, and the like. As the use of SCR's and transistors emerged, solid-state circuits using transistors, electronic amplifiers, and the like were utilized to implement feedback control circuits. More modern power sources make use of complex digital and analog integrated circuits to perform control functions. The latest development has been the increasing use of imbedded microprocessors in welding power sources and associated equipment to provide more sophisticated levels of control. Some welding equipment has advanced to the point of using keypads and computer displays for operator interfacing. The computing power of the microprocessor is leading to greatly increased sophistication in the type and manner of controls that can be applied to the arc welding process. These systems provide great promise in the future of arc welding technology.

Figure 6.21 shows a microprocessor controlled inverter-based welder for GMAW, FCAW, and SMAW which has the capability to store welding procedures and pulse waveforms for pulsed GMAW.



Figure 6.21: Microprocessor Controlled Inverter-Based Welder
(Photo courtesy of Lincoln Electric Company)

Section 7: Arc Starting Systems

Arc Starter Circuits – HF

Initiating of a welding arc requires that electrical breakdown be achieved (See Section 4). This can be accomplished by the application of a sufficiently high voltage between the electrodes to exceed the sparking potential. Gas tungsten arc welding often employs a momentary application of high voltage via either a high frequency or impulse type voltage generator to achieve breakdown. *High frequency*, or “HF”, systems create a continuously and rapidly fluctuating high voltage. This high voltage/low current either creates, or supports an ionized path through the gas media between electrodes. It is relatively easy to generate such a voltage with a *spark gap generator* circuit, and couple it to the welding electrode (Figure 7.1).

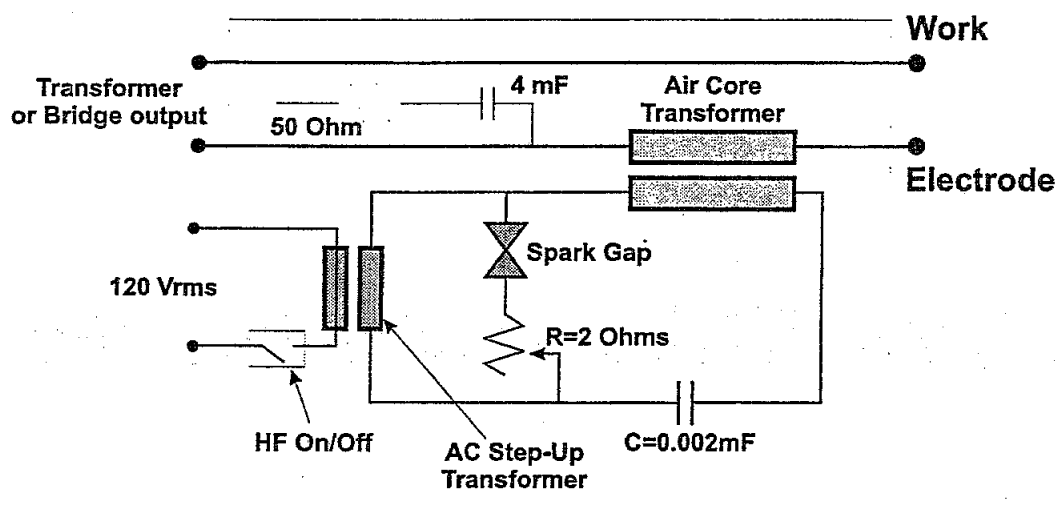


Figure 7.1: Arc Starter Circuits - HF

In high frequency systems, incoming AC line voltage is stepped up to several thousand volts by a transformer. This voltage is supplied to a *spark gap* in parallel with a capacitor. The capacitor is alternately charged by the transformer voltage and discharged as the spark gap breaks down. This occurs at tens of thousands of times per second. The impulses of current flow are coupled through a transformer, which produces high voltage spikes onto the welding power source output leads, sufficient to produce breakdown of the welding arc gap. This produces crackling, filamentary arcs between the electrode and work piece followed by arc starting.

The series RC filter across the input power source leads shorts the high frequency to bypass the power source and prevent the high voltage from damaging internal power source components.

A circuit is usually used to sense the arc and turn off the high frequency unit. In some applications the high frequency is left on continuously to “stabilize” the arc. This is primarily used when operating the arc with sinusoidal AC.

Arc Starter Circuits – Impulse

Another method of initiating an arc is with a high voltage impulse. These are called *impulse* type starters (Figure 7.2).

Impulse systems create a sudden single spike of voltage. One method is similar to that in an automobile ignition system. Repeated voltage spikes may be generated until an arc is achieved.

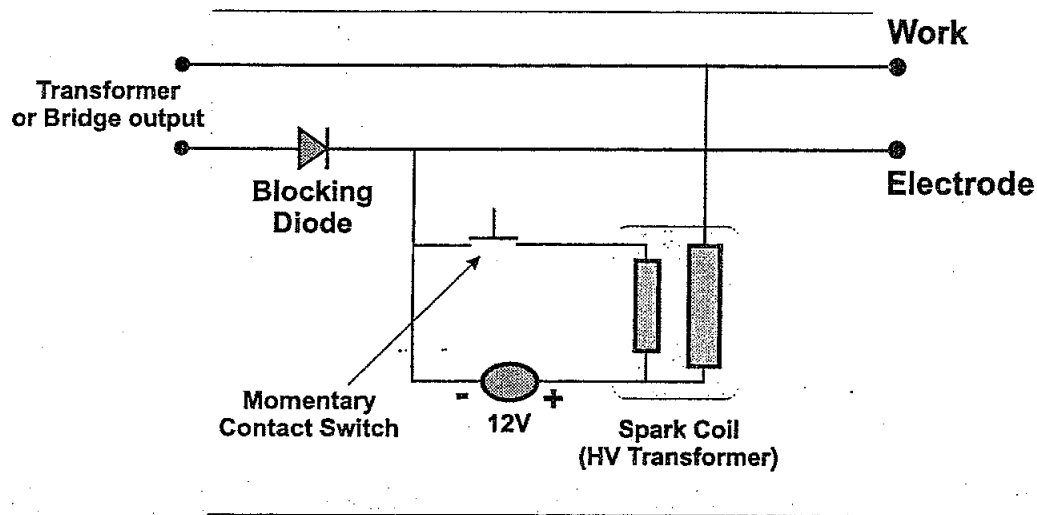


Figure 7.2: Arc Starter Circuits - Impulse

Both impulse and high frequency systems are effective and relatively safe, but they radiate large amounts of electrical noise which can cause a variety of problems with nearby electrical and electronic equipment. Personnel with pace makers or other electrical health devices should consult their physicians before being allowed to work in the area of high frequency equipment. Impulse systems produce somewhat less electrical noise because they do not operate continuously as do high frequency systems.

Starting by Shorting

The most common method of creating electrical breakdown for initiating welding arcs is to create a momentary electrical short between the welding and work electrode. This is also sometimes referred to as a *touch* or *scratch* start. Touch starting is always used with consumable electrode processes such as shielded and gas metal arc. For SMAW and GMAW, when the short is created, followed by the pulling back of the electrode to create a gap, the arc is said to be *drawn*. Arc starting by this method may be used with gas tungsten arc welding - GTAW (although special precautions may be necessary to prevent contamination). See Figure 7.3.

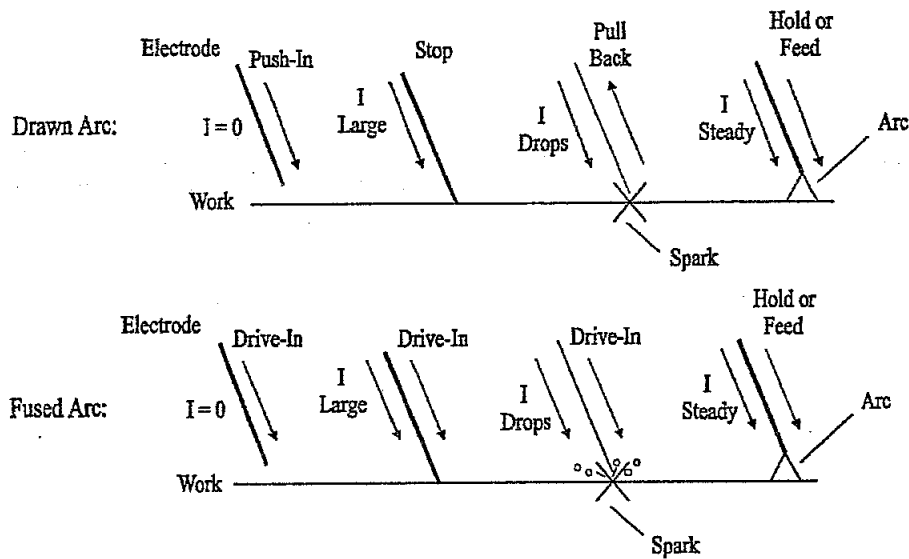


Figure 7.3: Starting by Shorting

An arc start by *fusing* is created when the gap occurs by vaporization of the metal forming the short. This is typical of processes with a mechanized wire feed such as gas metal arc where the electrode wire is fed forcibly into the work piece and constant voltage power is used. Drawing or fusing results in a relatively violent process in which large currents flow suddenly into the short from the constant voltage welding machine, producing rapid heating of the points of contact. The material at the point of contact rapidly melts and vaporizes. The loss of material from vapourizing produces a gap in which electrical breakdown initiates. Considerable *art* is employed in the design of equipment for providing adequate reliability and control of the initiation of the arc by shorting.

Mechanism of Arc Initiation by Shorting

From a physics standpoint, the superheated and vaporized metal emanating from the short produces a readily ionizable source of gaseous material as the short breaks and a gap forms (Figure 7.4). High gas temperatures in the gap, together with the low ionization potential of metals and other vapors, may be sufficient for the production of some *thermal ionization*. As the short disintegrates, the open-circuit voltage of the power source becomes available across the instantaneously small gap created as the molten metal bridge disintegrates. This produces a favorable condition for arc initiation. Additionally, and perhaps most important, series inductance in the power supply responds to the sudden drop in shorting current (as the short breaks) with a surge of inductively generated voltage which further contributes to achieving the necessary breakdown voltage. (This latter effect is the source of sparks that are observed when pulling the plug on any live electrical equipment.)

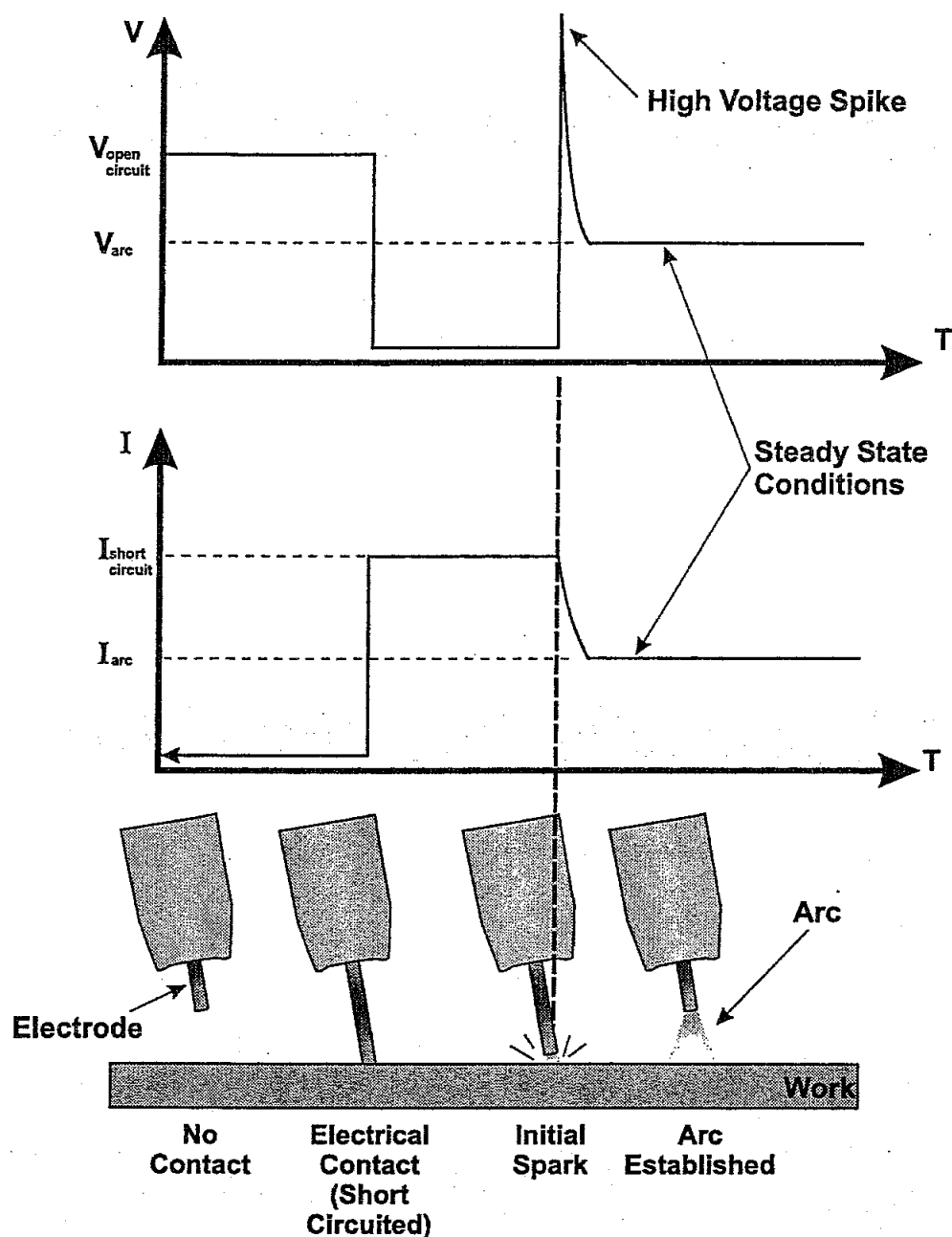


Figure 7.4: Mechanism of Arc Initiation by Shorting

It is known that higher open circuit voltage capability of a welding machine, as well as increasing series inductance in the welding machine output, has an enhancing effect on arc initiation. Low ionization potential materials added to the fluxing of electrodes also improve starting.

Section 8: Special Process Control Features

Pulsing

Welding machines are most commonly designed to deliver either steady DC output, sinusoidal or square wave AC for special applications (e.g., GTA welding of some materials). Pulsing types of output have been found useful in many welding applications (**Figure 8.1**). Pulsing involves the rapid altering of voltage and/or current between high and low values, without changing polarity.

Pulsing can be accomplished with more modern designs of machines with electronic feedback control. This is accomplished by supplying a signal for the desired output to the feedback circuit which pulses between two levels. The output of the welding machine will follow the pulsing input to the extent that the control circuit and power control element is capable.

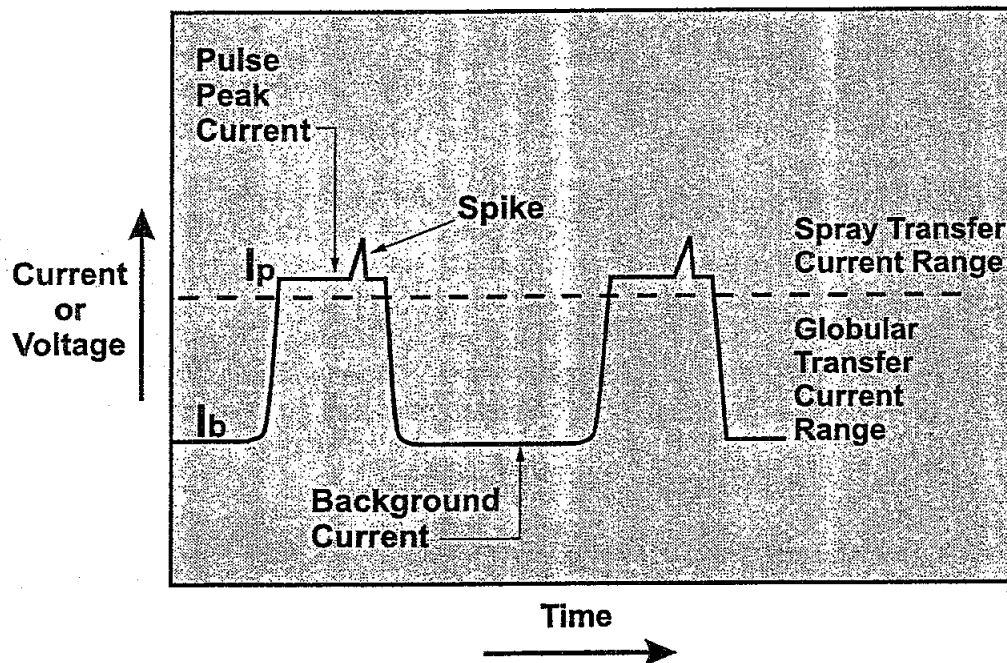


Figure 8.1: Pulsing Output (eg. GMAW)

Pulsing became a reality with the development of SCR machines with electronic feedback. Pulsing rates are limited with SCR controls due to the relatively slow control rate inherent to switching of single or three-phase waves. Pulse rates are limited to several times per second. Early transistor controlled machines (linear and switching types) were capable of rates of 10's to 100's of pulses per second. Inverter machines have since emerged and become the power source of choice which can easily provide accurately controlled pulse waveforms to very high frequencies. Pulsing has therefore become a much more commonly used variant of arc processes.

Pulsed GTAW

Pulsed GTAW involves pulsing of the arc current between low and high values at relatively slow rates of one to ten pulses per second. GTAW pulse rates can be achieved with older SCR technologies and with transistors. Vintage 1970's and 80's power supplies were sometimes provided with this capability. Typically, GTAW pulsing parameters are the pulse and background current levels, and the pulse and background times. The objective of pulsed GTAW is to produce a pulsating weld pool. A pulsating weld pool which grows and shrinks significantly with each pulse. The result is a weld similar to overlapping arc spot welds. Some advantages are found with regard to greater depth of penetration relative to heat input, and also solidification characteristics of the molten metal which may improve properties of the weld. Pulsating current may be synchronized with pulsating travel and pulsating wire feed in more elaborate systems. The precise benefits of pulsing with GTAW are sometimes debated.

Pulsed GMAW

Pulsed GMAW involves the rapid pulsing of power source voltage and/or current. Pulse frequencies are typically in the hundreds of pulses per second. This rate of pulsing was achievable with early transistor machines, but only became realistic on a broad scale with the emergence of inverter technology. Many modern GMAW welding machines thus have pulsing capability.

The purpose of pulsed GMAW is to control the metal transfer with pulsing. This results in controllable spray transfer at currents below that which can be maintained with steady DC current. The objective is to provide enough pulse current, for the proper length of time and rate, such that a small drop can be detached instead of the large glob of liquid (in globular transfer) that would develop and drop off after an extended period without the pulse. Peak and background voltage/current are important new parameters, along with peak and background pulse times. These are adjusted to values which give the desired metal transfer characteristics. Much development has gone on to determine the proper and best pulse characteristics. Manufacturers often build the pulsing characteristics into the machine, such that it will give optimum results for particular applications.

The desire for more precise and sharp pulses of current brings into play the minimization of inductance in the welding circuit. **Even the inductance created by the loop made by the welding leads can degrade pulsing performance of the latest of machines.**

Synergic Pulse

Synergic control has been mostly developed for use with pulsed-GMAW systems, since pulsing provides a number of additional parameters to be set. For instance, not only must desired voltage and wire feed be provided, but also peak and background voltages or currents, and times. Synergic machines incorporate these relationships into computer programs that can be selected by the user, minimizing the amount of set-up, and trial and error, that is required. Use of synergic controls with pulsed-GMAW has been important to allowing it to be more widely adopted.

Section 9: How to Select a Welding Power Supply

The range of arc welding power sources has increased significantly over the last few years. The wide selection of machines can be confusing, and the user must be systematic in making the most appropriate choice for their application. The objective of this section is to outline the most important factors to be considered when making a choice of equipment. These include:

- Primary application: material and thickness, and welding process or range of processes
- Required current range, DC, AC or AC/DC, power source characteristic
- Required duty cycle
- Type of power available in the shop - or field application
- Special features required - welding sequence control: slope up or down, waveform control, pulsing, square wave, dynamic control, pre-programmed systems, arc starting, control of shielding gas and water cooling, motion control
- Weight, size and portability requirements
- Robustness and reliability
- Complexity
- Interface to mechanized or robotic equipment
- Suppliers, spare parts, service, ease of repair, training
- Capital cost, return on investment, and electrical efficiency

Primary Application

The first requirement in selecting a power supply is to determine the primary application. The user must determine whether to select a machine which will cover a range of thickness and materials, and even processes, or whether the prime need for the machine is for a specific application. With the advent of modern electronic control, it has become more feasible to construct machines which will operate with a variety of processes. However, the additional cost of these multi-process machines must be weighed against lower cost equipment designed for a specific process. Some processes are easier to combine than others - for instance GTAW and SMAW both typically use a constant current power source characteristic, and hence, even before electronic control was available, power supplies could be constructed which could be used on both processes. The choice of equipment may also be linked to the choice of process: if capital cost is a major issue, then basic transformer or transformer rectifier equipment can be used with SMAW for a very wide range of welding applications. Duty cycle - percentage arc on time - and hence, productivity is likely to be lower for SMAW than for most other process, but in some cases the advantage of versatility may be more important than productivity. On

the other hand, if all the applications involve welding mild steel, then the GMAW process will produce a higher duty cycle, particularly for thin sheet applications.

Required Current Range, DC, AC or AC/DC, Power Source Characteristic

In welding, bigger is not necessarily better, and a machine with a high maximum current may not have the same precision of control or arc stability which would be desirable for welding thin materials. The current range should be chosen to match the requirements of the most common applications in order to best match the process to the power source. If applications covering several current ranges are common, then it is possible to select machines which can be switched between one current range or another.

The choice of DC and AC is generally determined by the choice of process, although some processes may offer options. For instance, SMAW electrodes may be designed for use with DC or AC or both. GMAW welding is performed with DCEP, and for FCAW direct current is also used although some wires are designed to be used with DCEN rather than DCEP. Most GTAW is performed with DCEN, but AC is often used with aluminum in order to take advantage of cathodic cleaning of the surface oxide in the electrode positive part of the cycle. Inverter based power supplies for GTAW are now offering the ability to increase AC welding current frequency. This can offer the advantage of increased arc focussing and the use of a pointed, alloyed tungsten to more readily make small welds or improve penetration and control in thicker parts.

The power source characteristic must also be matched to the process requirements, and therefore many power supplies will have variable slope to accommodate a variety of process applications. For instance, with SMAW used with high currents and large diameter electrodes, a steep voltage-ampere curve is desirable, while for out-of-position welds a flatter volt-ampere curve enables the skilled welder to adjust welding current by changing arc length. Modern electronically controlled power supplies may offer additional features.

Duty Cycle

The duty cycle of a welding power supply is the ratio of arc-on time allowed in a specified test time. In North America, the test time is 10 minutes, so a machine with a duty cycle of 60% can deliver its rated output for 6 minutes out of every 10 minutes. The use of the duty cycle concept allows power supply manufacturers to make equipment at lower cost than would otherwise be the case. During the operation of the power supply, the transformer and associated components heat up, and the "off" period of the test time allows the machine to cool down before it is operated again. It is important to note that 60% duty cycle does NOT mean that equipment can be operated continuously for 36 minutes in an hour, but for six minutes in ten. Prolonged use at rated load in excess of the duty cycle will cause thermal cut-outs to disable the machine (if they are present) or if the equipment is not thermally protected, will lead to overheating, insulation breakdown, and failure.

Power supplies are rated according to NEMA (the National Electrical Manufacturers Association) Standard EW1 ("Electric Arc Welding Power Supplies") in one of three classes:

- Class 1: 10 ranges of rated current output from 200 amps (max.) to 1500 Amps (max.), 60%, 80%, or 100% duty cycle
- Class 2: 7 ranges of rated current output from 150 amps (max.) to 350 amps (max.), 30%, 40%, or 50% duty cycle
- Class 3: Rated current output in ranges of 180 to 230 amps, 235 to 295 amps, duty cycle 20%.

Class 3 AC transformer welding machines are popular for use in rural areas or as hobby welders, since they are generally designed to operate on available utility power lines, at 240 volts. They are known as utility or farm welders. Class 2 machines are not very popular, and most machines designed for industrial use come under the NEMA Class 1. With increasing use of mechanized and automatic welding, the use of 100% duty cycle machines is increasing.

Utility Power Availability

Most power supplies sold in North America are provided with taps to match different input voltages. However, this is not always the case, and some machines require a specific input voltage.

The electrical input requirements specified for NEMA Class 1 transformer arc welding machines operating at 60 Hz are:

200V 230V 460V 575V

Industrial three-phase power is supplied at 60 Hz in North America as follows:

- 208/120 V - Canada and U.S.
- 600/347V - Canada only
- 480/277V - U.S. only

Residential (single-phase) power is supplied in Canada at 120 and 240 V.

Care must be taken to ensure that the selected equipment will operate with available shop power.

For field use when utility power is not available, engine driven generators are the only choice. Air-cooled, gas driven alternators and generators are popular for general use. For heavy duty use water-cooled diesel alternators/generators are used. Engine driven alternators/generators are available with a range of capabilities, including different power supply characteristics, DC/AC power, built-in compressors and auxiliary power for running other equipment. In some cases, output power has been customized to the application, for instance, equipment is available which has an optimum power supply characteristic for cross-country SMAW pipe welding.

Additional Features

There are ranges of additional and special features which may be desirable or essential for certain applications. These include slope up and slope out of current (slope out is sometimes called crater fill), pulsing of welding current and/or voltage, dynamic control of current and voltage waveform, waveform shape, and pre-programming, arc starting, control of shielding gas and water cooling, motion control. These features have already been described in earlier sections, and the user should carefully evaluate the need for such features in his welding application. Some features will be desirable in some cases and less so in others. For instance, waveform pulsing in GMAW may be a desirable feature to enable positional welding while minimizing spatter, but may be less desirable if all welding is being performed in the flat position above the transition current for spray transfer. Other features may be very useful for some applications - the introduction of square wave AC waveforms for welding aluminum has made welding of aluminum somewhat easier. A recent trend for power supplies is to be pre-programmed with welding schedules where only the material and desired weld size need to be specified by the user. Here, the initial work of optimizing the process for certain applications has been performed by the equipment supplier.

Most modern power supplies have options for digital readout of output parameters: voltage, amperage and in the case of pulse GMAW, wire feed speed. These features are valuable tools when assessing the performance of a welding station. The visual confirmation of operating parameters is an invaluable tool when assessing a welding station. In this regard, the digital meters must be calibrated and verified regularly.

Weight and Portability

One of the most obvious developments which has resulted from the introduction of inverter power supplies has been the substantial reduction in weight and size of power sources. The small size of the high frequency transformers for inverter power supplies not only brings increased portability for the user, but also reduces the cost of expensive raw materials in the power source. These small power sources can now be moved around a job site with much greater ease than was the case in the past. The smaller power supply also consumes less manufacturing space when compared against machines of the SCR generation.

Robustness and Reliability

Older power supplies tend to have very simple electro-mechanical designs, with few components which are prone to failure. It is common to see power supplies over 20 years old in daily use, with little or no maintenance required. Robustness and reliability are key components in any power supply, and modern electronically controlled power supplies are clearly of more complex design, and have electronic components which do have indefinite life. Manufacturers go to considerable lengths to make their equipment as reliable as possible, and the user should evaluate the anticipated reliability of power supplies in relation to his work environment.

Complexity

Modern power supplies may have a great deal of versatility, and some equipment has many controls or programmable features which can be implemented. The user should balance the additional versatility against complexity, in relation to the knowledge of the welders and operators who will use the equipment. Sophisticated technology will not be utilized to its full potential or may even be made to appear "not effective" without matching knowledge. In this regard, upgrade training of welding personnel may be a factor in selecting a particular technology.

Interface to Mechanized or Robotic Equipment

With the increasing use of mechanized and robotic welding equipment, it has been increasingly necessary for interfaces to be provided. As a minimum, these interfaces allow the arc to be started, and in many cases make close control of welding parameters possible from the robot or automated equipment controller. Systems suppliers will usually supply integrated systems, but users may have a need to retrofit power supplies to automated systems, and will need to ensure the appropriate interfaces are available.

Suppliers, Spare Parts, Service, Ease of Repair, Training

Choice of supplier is an important factor in choosing a power source. The supplier should be able to advise on what spare parts should be held by the user, and should have inventory of parts, and technicians able to perform more complex repairs. In addition, suppliers will often make equipment available for evaluation, and should be able to organize training if the equipment is complex, or the process is new to the user.

Funds Available, Return on Investment (ROI), and Electrical Efficiency

Users should evaluate the return on investment which new equipment will provide, including any productivity gains which the equipment will make possible. **Most evaluations of welding costs conclude that labor costs are by far the largest component of overall costs in welding, and therefore, the cost of the equipment should be evaluated in relation to the benefits it will provide.** One of the "unseen" benefits of modern equipment is a significant improvement in electrical efficiency. Electrical efficiency may be described as ".....the ratio of the amount of power or work obtained from a machine to the amount of power required to operate it". It is not uncommon for old equipment to be operating at an electrical efficiency lower than 50%, while some modern systems can exceed 90% electrical efficiency. The savings in electricity costs can be a significant factor in calculating the ROI in new welding equipment.

Section 10: Practical Application

Setting Up a System

Installation of a welding systems must be done in accordance with the manufacturer's instructions and in compliance with local and national codes. Applicable standards include:

Canada:

- CSA C22.1 Canadian Electrical Code, Part 1
- CSA C22.2 No. 0 General requirements - Canadian Electrical Code, Part II
- CSA C22.2 No. 0.1 - Bonding and Grounding of Electrical Equipment (Protective Grounding)
- CSA W117.2 - Code for Safety in Welding and Cutting (Requirements for Welding Operators)

USA:

- ANSI/NFPA 70 - National Electrical Code
- ANSI/ASC Z49.1 - Safety in Welding, Cutting and Allied Processes

The various safety codes and standards include requirements for connections, cabling, fuses, and grounding. **All electrical work must be performed by qualified personnel.** Welding power supplies are connected to high voltages, and incorrect installation can lead to injury or death, and damage to equipment.

Once the electrical installation has been completed, it is usually the responsibility of the welder or operator to set up the system for welding. Again, the manufacturer's handbook is the primary source of information relating to set-up and operation of the equipment. A systematic approach should be followed in setting up a system for a new application. Cables of adequate size must be used, and care must be taken to ensure the correct polarity is used, and the tight connections are made. The set-up should be checked to ensure that proper grounding is in place. All the other features of the system should be checked that components are properly connected and are in good condition: Gas bottles should have adequate pressure, gas systems free of leaks, regulator set at correct level, wire feeder set-up with correct wheel pressure, contact tip and nozzle in good condition, correct size of electrode, and good electrode condition for GTAW.

Welding should be carried out in a dry, well-lit and ventilated area, and cable runs must be direct and organized to prevent a tripping hazard. Appropriate screens must be placed to shield other personnel from arc glare, and of course the welder must use appropriate protective equipment. (See GCIL Module 1: Welding Health and Safety).

Grounding

Special care must be taken to ensure that the workpiece is correctly grounded, and this is an area where confusion exists, since the work lead and work lead clamp are sometimes incorrectly referred to as "ground lead" and "ground clamp". When possible, the work must be connected to the power supply by a separate cable, the work lead. Grounding is necessary to stabilize voltage at the work to ground potential under normal conditions, to help prevent accidental shock when equipment is misconnected or insulation fails, and to protect against high voltage under abnormal conditions such as lightning strikes or line voltage surges.

Proper grounding can be achieved in several ways. The workpiece may be placed on a grounded metal floor or platen, or be connected to a grounded building frame or other satisfactory ground. (Note that electrical conduits are not suitable as grounds). The work lead may be grounded at the power supply by connecting the terminal to the grounded power source enclosure. However, the cable used for this connection must be of smaller diameter (at least two wire gages higher) than the grounding conductor, and the terminal must be marked to show that it is grounded.

It is important to avoid multiple grounding. Multiple grounding may result in ground cable carrying welding current at a higher amperage than the ground conductor can carry safely.

When possible, the work lead should be a separate cable from the work to the power supply. Chains, wire ropes, cranes, and hoists must not be used to carry welding current. If it is necessary to use the structure of a building or other fabrication as part of a welding current return circuit, it must be checked to ensure that proper electrical continuity exists.

If more than one welder is working on a structure, DC machines must be connected to the same polarity, and single-phase AC machines must be connected to the same phase. The danger exists that the no-load voltage between two electrode holders may be up to two times higher than the voltage between the electrode holder and ground.

It is sometimes possible to parallel power supplies when the current output from one machine is insufficient. Power supplies of identical type and size should be used, with connections to the same terminals and the same settings on both power supplies. Short cables of equal length should be used to provide common terminations to which the electrode and work leads can be attached. If AC transformer rectifier welding power sources are paralleled, each welding power supply must be connected to the same phase, and the output should be checked to ensure that the connection has been made correctly. It is also possible to parallel engine driven DC power supplies, but not engine driven AC power supplies.

Cable Size and Length

Welding cables are designed to be flexible and have a tough (usually rubber or plastic) covering to provide insulation and to protect against the rigors of welding service. Standards which cover the manufacturer of welding cables include CSA Standard C22.2 No. 95 "Arc Welding Cables".

The total welding cable length is the length of the electrode lead (the cable between the power source and the electrode), plus the length of the workpiece lead (the cable between the work and the power source).

Welding cables are normally made of copper, but aluminum is also occasionally used. If aluminum is used, cable diameter must be increased by 2 AWG (American Wire Gauge) sizes than would be used with copper to compensate for the lower conductivity of aluminum, and terminations also require additional attention. Aluminum cable is not normally used for high current applications.

Cable is sized to prevent excessive temperature rise in the cable, and to avoid high loads on the power supply from the resistive loss in the cable.

The recommended sizes in AWG for copper cable are given in the following table (Table 10.1).

Welding Current, amps	Length of Cable: Electrode Lead Plus Workpiece Lead					
	50 ft 15 m	100 ft 30 m	150 ft 46 m	200 ft 61 m	300 ft 91 m	400 ft 200 m
75	6	6	4	3	2	1
100	4	4	3	2	1	1/0
150	3	3	2	1	2/0	3/0
200	2	2	1	1/0	3/0	4/0
250	2	2	1/0	2/0	4/0	-
300	1	1	2/0	3/0	-	-
350	1/0	1/0	3/0	4/0		
400	1/0	2/0	3/0			
450	2/0	3/0	4/0			
500	3/0	3/0	4/0			

Duty cycle up 60%, DC

For duty cycle above 60% or AC use next size larger cable.

Table 10.1: Recommended Cable Sizes (Copper)

The need to increase cable size for long cables is to avoid too large a load on the power supply from resistive losses in the cable. The following table shows the voltage drop per 100 ft (30 m) for a range of welding currents (Table 10.2).

Current	Voltage Drop per 30m (100ft) for AWG Size					
Amps	#2	#1	#1/0	#2/0	#3/0	#4/0
100	1.56	1.24	0.98	0.78	0.62	0.49
200	3.12	2.48	1.96	1.56	1.23	0.98
300	4.68	3.72	2.95	2.38	1.85	1.47
400		4.96	3.93	3.12	2.47	1.96
500			4.91	3.89	3.09	2.45
600				4.67	3.71	2.45
700					4.32	3.43
800						3.92
Conductor dia: in.	0.2576	0.2893	0.3249	0.3648	0.4096	0.460
Conductor dia: mm	6.543	7.348	8.252	9.266	10.404	11.684
Resistance per foot, ohms	0.0156	0.0124	0.00982	0.00779	0.00618	0.00490

Table 10.2: Voltage Drop Per 30m (100ft)

Cable length should be minimized where possible. In addition to the resistive load, the cable has self inductance, and **when pulsed welding is used, for instance in pulsed GMAW, very long cable will result in a change in waveform shape.** Sharp edge pulses will tend to be a more rounded or sine wave appearance, and this may well affect the performance of the welding process.

Portable applications make long cables necessary. The cables stored on the sides of a truck form a coil. If the coil has no 'core' the inductive effect may be minimal - except for inverter power supplies - supplies with higher than 60Hz output. Wrapping the cables on a ferromagnetic core - old steel wheel rim - creates significant inductive effect. The cables must be stored in such a manner as to not intensify the inductive effect.

Calibration and Monitoring

The adoption of formal quality systems has led to an increased requirement to calibrate welding equipment, and to monitor welding parameters during welding. Calibration can be defined as the determination and adjustment of errors of a measuring instrument. Thus, although welding equipment cannot be calibrated, the instruments on the power source can be calibrated. In order to carry out a calibration, a resistive load bank is used, which is designed to provide a stable load to the power supply at prescribed load conditions. Use of the arc as a load in calibration procedures is generally not satisfactory because of fluctuations in current and voltage.

The instruments used in the calibration, typically to record current, voltage, wire feed speed and travel speed, must be of prescribed accuracy, and traceable to National Standards. The accuracy required from the calibration will depend on specification or standards to which the calibration is being conducted.

For the purposes of establishing and verifying procedural parameters the welding station must be evaluated as a unit. (Power source, feeding system and power cables). Changes to the components of a system will effect the performance and accuracy of system instruments. Average current measurements can be made with calibrated Hall effect devices and compared to machine readings. Average current measurements can be made at any point in the output circuit since current through a series circuit is common at any point. Pulsed systems cannot be evaluated in this manner - the manufacturer must be contacted for the method of calibration which usually involves use of an oscilloscope.

Wire feed speed, travel speed and arc voltage have become increasingly the parameters which exert the greatest influence on repeatability and therefore current trends are to concentrate on these variables. Voltage measurements must be made as close to the arc as possible to avoid voltage drop through the power circuit. In this regard, it may be advisable for the company to establish a standard procedure for voltage output measurement and verification. In this manner the repeatability of welding procedures can be maintained.

There are a number of commercial instruments which can be used for calibration, and the same or similar instruments can also be used for monitoring and recording welding parameters. The simplest devices are voltmeters used to measure voltage. Voltmeters can also be used with a calibrated current shunt or resistive load to measure current. However, both current shunts and resistive load must be connected in series with the welding circuit, and hence, devices based on the "Hall Effect" are commonly used to measure current, since the Hall effect sensor is placed close to the welding cable. Tachometers and other devices can be used with rolling wheels to measure wire feed speed and travel speed during welding. Welding parameters can be recorded using strip chart recorders, and there are also commercial instruments which will monitor and print average welding parameters during a weld. More advanced systems include microprocessor based systems, which are not only able to capture average welding parameters values, but can also record at high frequencies, up to 40 kHz, and this can be used to study the voltage and current waveform in detail.

Electrical Interference From Arc Welding

The fact that current and voltage can change rapidly during welding means that electromagnetic emissions can be radiated from the welding equipment. These electromagnetic waves are transmitted through the air like radio signals, and can interfere with other equipment. In particular, computer controlled devices such as numerically controlled machine tools may be affected by emissions from welding equipment. In addition, when high voltage/high frequency devices are used to assist in starting GTAW or PAW arcs, very high levels of emissions can be produced. There are also other routes for electrical interference to be transmitted. For instance, conducted emissions can be fed down the electrical supply cable into the mains supply.

Problems are most likely to occur with the use of HF/HV (high frequency/high voltage) systems for arc starting. NEMA Standard EW1 includes methods to reduce emission levels for HF/HV which will also be effective in reducing emissions from arc welding generally. These are summarized as follows:

- Avoid unshielded miscellaneous conductors within the welding zone. This means that all lighting, power, telephone and other conductors within the welding zone should be enclosed in rigid grounded metallic conduit (flexible helically wrapped conduit is generally not suitable).
- Keep welding leads as short as possible (less than 25 ft) and position leads close together and as close to the ground as possible.
- Provide a low impedance earth to ground the power supply enclosure (and the HF/HV enclosure if that is separate).
- Locate equipment within an electrically bonded and grounded metal building.

Troubleshooting

Many of the problems which occur in arc welding can be solved by adopting a systematic approach to identify the source of the problem. The purpose of this section is to outline some of the possible causes of problems, and their solution. It is important to distinguish between equipment problems, and *process or set-up problems*. Issues of process and set-up are very often the cause of welding problems, and can usually be rectified by the operator. Faults with the welding equipment itself will usually require qualified personnel to correct. Fortunately, welding power supplies are very reliable, and indeed power supplies of robust and simple design from 30 or 40 years ago have few parts to fail and can still be found in daily use. Modern electronic power supplies may have electronic or microprocessor boards which can fail, and in these cases it is possible for trained personnel to replace the boards to achieve a repair.

Basic preventative maintenance is the key to longevity and reliability of welding equipment. Following the maintenance items identified by the equipment manufacturer usually involves a few simple steps such as periodic cleaning. **Figure 10.1** shows a power supply in need of cleaning. It is important to remember that the 'dirt' inside a power source is very likely electrically conductive. While this is important to avoid in analogue equipment, electronic supplies are sensitive to alternate conductive paths, especially circuit boards. **FOLLOW MANUFACTURERS RECOMMENDATIONS - DISCONNECT POWER SUPPLY. NEVER REMOVE THE HOUSING OF AN ELECTRICAL DEVICE WHILE IT IS CONNECTED TO LINE POWER.** Electrical maintenance should always be carried out by qualified personnel.

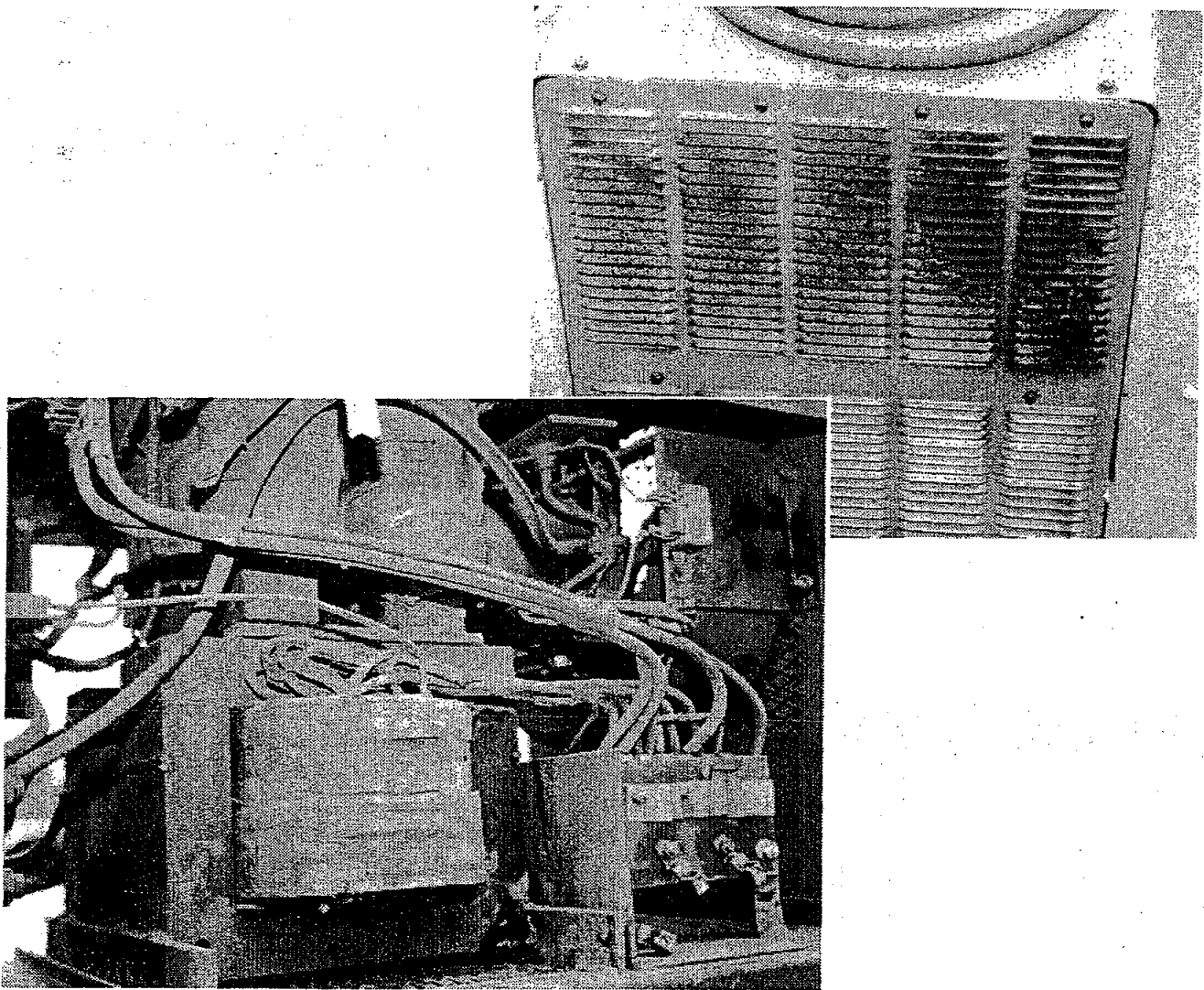


Figure 10.1: Power Source in Need of Cleaning

Fault Types

Faults may be classified as:

1. **Improperly adjusted process settings:** for instance, in GMAW, if the voltage is set incorrectly, the arc may not be stable and excessive spatter may be produced, or if the gas flow rate is set too low (or too high) then again the arc may be unstable, and gross porosity may be evident. The equipment and the process are working correctly, but the settings are not adjusted to produce a satisfactory weld.

2. **Incorrect operation or failure of ancillary equipment:** for example, too low a wire feed roller pressure may result in wire slippage, leading to burn-back or a weld nozzle clogged with spatter may lead to a heavily oxidized weld. The welding parameter settings may be correct, but some feature of the ancillary equipment is not operating correctly.
3. **Power source electrical or electronic fault:** some aspect of the power supply or its control system has failed, and must be repaired. These failures are least common, but the equipment must often be sent to an authorized service agent for repair.

Systematic Identification of Equipment Problems

In tracking faults, it is important to be systematic in tracing the root cause of failure, and it must be recognized that one type of fault may have more than one possible cause. The trouble shooting chart in the next section may assist in tracing generic faults, but the primary source of information relating to a specific power supply should always be the manufacturer's handbook. Suppliers often provide detailed information on tracing faults, and may also provide test procedures to evaluate the performance of equipment.

The operation of a welding system can be evaluated by systematically checking through the individual components. (Note that a simple voltmeter and clip-round ammeter are necessary to perform some tests - and that any test involving high voltage electricity should be performed by suitably qualified personnel).

Input Power: Check: fuses intact, electrical connections to power source correctly connected, supply voltage matches power supply requirement.

Output Power: Internal fuses intact, thermal overload not tripped, open circuit voltage in appropriate range, operating voltage in appropriate range.

Cables and Connections: Correct size cables used, of appropriate length; good connections between cables, power source, torch, workpiece, appropriate grounding, correct polarity.

Wire Feeder: Motor operating, correct contact wheel pressure.

Wire Conduit: Clean and intact.

Contact Tip (GMAW, FCAW, SAW): Tight (good electrical contact); not excessively worn.

Electrode Holder, Collet (GTAW, PAW): Tight, good condition.

Gas Shielding: Gas bottle pressure adequate, gas flow appropriate, nozzle clear from spatter, no leaks in line or torch.

Water Cooling: Adequate flow rate.

Some faults may be difficult to isolate, and if spare equipment is available, it is helpful to trace faults by swapping out or exchanging components.

Fault Finding Guide

In most cases, the manufacturer's handbook for a power supply will include detailed guidance for fault finding on that system, and should always be consulted. The guide below gives general guidance on fault finding equipment problems for a range of processes.

Symptoms	Possible Causes	Remedies
Power source dead	No line voltage	Check voltage
	Incorrect line voltage	Check voltage
	Line fuse blown	Check and replace
	Power source fuse blown	Check and replace
	Overload tripped	Reset
GMAW: Wire feeds but arc will not start	Power source fuse blown	Check and replace
	Welding cables loose	Tighten
	Contact relay failed	Replace
GTAW: Arc will not start	HV/HF failed	Replace
	HV/HF switched out	Use correct switch position
	Too large arc gap	Reduce arc gap
	Too large diameter electrode	Use smaller diameter
	Incorrect electrode material or poor condition	Use appropriate electrode, sharpen correctly
Arc starts, but stops after a period	Machine overloaded	Reduce welding current
	Duty cycle too high	Operate within equipment capability
	Power leads too small diameter or too long	Replace with larger cable
	Fan not operating	Check fan operation
GMAW/FCAW/SAW: Wire stops feeding	Drive roll pressure incorrect	Adjust pressure
	Wire feeder connection failure	Repair connection
	Drive motor/control board failed	Replace
	Torch liner dirty	Replace
	Contact tip restricted/bumback	Replace contact tip
GMAW/GTAW: Unstable arc/oxidation	Sharp bend in torch cable	Straighten
	Low gas cylinder pressure	Replace cylinder
	Incorrect flow rate setting	Adjust
	Leaks	Repair
	CO ₂ regulator frozen	Thaw - install heater
	Incorrect polarity	Change polarity

Section 11: Standards and Safety

Module 1 in this series provides a detailed review of many the safety factors which are important in Arc Welding. In this section, those features which are specific to arc welding power supplies will be considered.

It must be recognized that the high voltages associated with arc welding power supplies can pose dangers of electric shock which can cause damage, or be fatal. This is especially true on the primary side of welding power supplies, where the voltage is high enough to pose a high degree of risk. For this reason, it is emphasized that **only qualified personnel should make high voltage connections to arc welding power supplies.**

The voltages available on the secondary side of welding power supplies are not without danger. Welders and operators must always take appropriate precautions to avoid contact with the open circuit or operating voltage on the secondary side of a power supply, and should not become complacent about the risks involved.

The severity of an electric shock depends principally on the magnitude of the current and the part of the body through which it passes. A current of about 70 mA is enough to cause death. The magnitude of the current which can flow depends on the effective resistance of the body. When the skin is dry, the resistance between two points on opposite sides of the body is in the range of 10,000 to 1,000,000 ohms. However, when the skin is wet, the resistance may be 1000 ohms or less. Under these conditions, a voltage of only 80V would cause a current of 120 mA to flow, and as stated above, this is enough to cause death. For this reason, special precautions are necessary to reduce open circuit voltage if it is essential to work in water, or in damp areas. Useful protection is obtained by wearing of dry, insulating gloves and boots.

Canadian Standards Association (CSA) Standard C22.2 No. 60 "Arc Welding Equipment" provides detailed standards of manufacture and test of arc welding power supplies, and requires that the open circuit voltage for manual and semi-automatic arc welding machines shall not be greater than:

- AC arc welding power source – 80V rms
- DC arc welding power source with more than 10% ripple voltage – 80 Vrms
- DC arc welding power source with 10% or less ripple voltage – 100 V average.

These requirements are equivalent to those contained in The National Electrical Standards Association (NEMA) Publication No EW1 "Electric Arc Welding Powers Sources".

The International Standards CEI IEC 974-1, Part 1, "Welding Power Sources", specifies for environments without increase hazard of electric shock that the no-load voltage shall not exceed 113 V DC, or 80 V AC, 113 V peak. For environments with increased hazard of electric shock, this International standard requires that the rated no-load voltage shall not exceed 113 V DC, or 48 V rms AC (68 V peak). In some case, for instance in automatic welding when increased protection for the operator is provided, OCV may be 141 V peak DC, or 100 V rms AC (141 V peak).

Standards require that metal parts at OCV (open circuit voltage) have covering insulators to help prevent accidental contact, and that parts which cannot be insulated or protected (such as wire feeder components and welding wire in some systems) have a notice warning of the potential dangers of electric shock. The fact the high OCV is allowed by standards should not allow welders to become complacent. Electric shocks can easily be caused by OCV welding voltages, and in some cases have been fatal. Systems are only regarded as relatively safe if the system is double insulated or isolated, and the OCV is less than 30 V rms (42 V DC).

For situations where welding has to take place in damp conditions, safety devices known as open circuit voltage reducers (OCVRs) are available. These devices switch the high OCV out until the system detects a low resistance due to contact of the electrode with the work, when the OCV is re-applied.

The American Welding Society standard ANSI/ASC Z49.1, "Safety in Welding, Cutting, and Allied Processes" gives detailed advice on safety precautions to be taken in arc welding, and should be consulted for guidance. A summary of the main points relating to arc welding power supplies is as follows:

1. Operators of arc welding equipment must be properly instructed and qualified. Rules and instructions for operation and maintenance must be readily available.
2. Special care must be taken when working under electrically hazardous conditions. Non-conductive gloves, clothing, and shoes should be worn. Hazardous conditions include those where freedom of movement is restricted (cramped conditions), and situations where water or perspiration may cause hazards. In hazardous conditions, systems should be used to reduce the no-load voltage to less than 38 volts rms ac or 50 volts DC.
3. Labels shall be used to warn of hazards of the open circuit voltage is high than specified by NEMA Publication EW1.
4. Equipment shall not be used above the rated ampere ratings and duty cycles. Remember that duty cycle applies to a 10 minute period, so a 60% duty cycle means 6 minutes in every 10.

GUIDES AND EXERCISES

MODULE 5

POWER SOURCES FOR WELDING

To obtain maximum benefit from this module, we suggest that you follow this guide and complete the exercises as indicated. It is important that you work through the text methodically, studying each section thoroughly before moving on. The exercises are designed to give you an indication whether you have learned the material and can move on or whether you need to go back and study the section again.

Do the exercises honestly. They will not help you unless you take them seriously. If you get a question wrong, go back through the text until you understand where you have gone wrong and know the correct answer.

The length of time required to complete the module will vary from student to student. Find your own pace. Do not rush. Remember you are trying to teach yourself something, not win a race.

Some people like to underline sections when they read a text. We suggest that you use caution when you do this. What you think is important first time you read it may be different after reading it three times. We suggest you read a section three times thoroughly before highlighting anything.

The last exercise is designed to give you an indication of whether you are ready to take the GCIL closed book examination. The exercise questions are similar to the official examination. Do not take the examination until you feel you are ready and you may wish to study several Modules before taking the examination for each.

If you have difficulty with this module, do not hesitate to ask for help by contacting the Gooderham Centre for Industrial Learning at 905-542-2176.

Guide 1

Carefully study pages 1-35 and answer the following questions:

1. When GTA welding, a strong positive voltage is applied to the tungsten electrode because of its high melting point.
 - a) True
 - b) False
2. To initiate an arc requires high current and low voltage power.
 - a) True
 - b) False
3. How much current will flow through a resistance of 200 ohms when 100 volts is applied?
 - a) 0.5 amps
 - b) 5.0 amps
 - c) 2.0 amps
 - d) 20 amps
4. A generator consists of rotating conductors in a stationary magnetic field and an alternator consists of rotating magnetic field inside the conductor windings.
 - a) True
 - b) False
5. In a series circuit current may be accurately measured at any point because there is only a single path for current to flow.
 - a) True
 - b) False

Check you answers for accuracy. If any of your answers are wrong, re-study the guide subject until you understand it.

Guide 2

Carefully study pages 36-46 and answer the following questions:

1. Steep slope minimizes the change in current due to changes in arc length (constant current). In some situations a flatter slope is used to provide some change in current when arc length changes - a common preference when manually welding pipe joints.
 - a) True
 - b) False
2. What type of output current is usually required for GTAW?
 - a) very high open circuit voltage
 - b) high frequency open circuit current
 - c) constant current
 - d) low power factor
 - e) high duty cycle current
 - f) constant voltage
3. Constant current power supplies can be used, both in DC and AC.
 - a) True
 - b) False
4. A constant voltage power supply is required for GMAW process.
 - a) True
 - b) False

Guide 3

Carefully study pages 47-56 and answer the following questions:

1. Motor-generators are bulky and heavy, have many moving parts which are prone to wear and require frequent maintenance.
 - a) True
 - b) False
2. A transformer is a device which converts utility AC power to DC welding current.
 - a) True
 - b) False
3. A disadvantage of SCR control is that the output is very "choppy". The output is smoothed out by the addition of a bank of capacitors.
 - a) True
 - b) False
4. One of the simplest ways of controlling the output of a welding transformer is to change the efficiency of coupling. How can this be done?
 - a) slide a piece of wood between the primary and the secondary coils.
 - b) design the transformer with either a moving core or moving primary coils.
 - c) design the transformer with a number of taps to select different output curves
 - d) use the timed firing of SCR's to control total conduction time
5. A conventional diode placed in a circuit allows the passage of current in one direction only. A silicon controlled rectifier (SCR) operates slightly differently. How does it work?
 - a) an SCR conducts current in both directions until turned on and current flow is then prevented
 - b) an SCR is non-conductive until turned on and then allows current to flow in both directions
 - c) an SCR is non-conductive until turned on and then allows current to flow in one direction only until the flow of current stops
 - d) an SCR is a unique device which allows only AC current to flow

Guide 4

Carefully study pages 57 to 75 and answer the following questions:

1. In a CC power source, the steeper the slope the less then current will vary.
 - a) True
 - b) False

2. What is the term for voltage measure across the output terminals of a welding machine when no current is being drawn?
 - a) diode voltage
 - b) operating voltage
 - c) open circuit voltage
 - d) terminal voltage

3. The maximum open circuit voltage of CC power source is limited to 80 volts for safety reasons.
 - a) True
 - b) False

4. High short-circuit current tends to produce violent shorting reactions, producing spatters, and low short-circuit current leads to sticking of the electrode.
 - a) True
 - b) False

5. Addition of inductance on the DC output side makes metal transfer smooth and helps reinitiation of the welding arc.
 - a) True
 - b) False

Guide 5

Carefully study pages 76 to 85 and answer the following questions:

1. What is the high frequency unit used for in GTAW or PAW power sources?
 - a) to preheat the joint
 - b) to reduce the overall power efficiency
 - c) to promote deeper penetration
 - d) to provide arc starting and arc stability
2. Inverter based power supplies for GTAW are now offering the ability to increase AC welding current frequency. Increasing the frequency can improve arc focusing when using alloyed tungstens for aluminum welding.
 - a) True
 - b) False
3. In high frequency systems, incoming AC line voltage is stepped up to several thousand volts by a transformer. Select the correct statement.
 - a) high frequency systems are limited to less than 4000 volts for safety reasons
 - b) the spark gap needs to be a least 75mm (3") wide for the spark to jump far enough to create the crackling arc
 - c) high frequency systems output high voltage buy only low current
 - d) high frequency systems only work with DC arcs
4. Power supplies are selected by process only without consideration of material type and thickness.
 - a) True
 - b) False
5. In welding, bigger is better and a machine with high maximum current is best for all industrial applications.
 - a) True
 - b) False

Guide 6

Carefully study pages 86 to 98 and answer the following questions:

1. The length of welding cables has little or no effect on the performance of the equipment.
 - a) True
 - b) False

2. Welding cable sizes are designated according to the American Wire Gauge. For example, no. 6 cable is bigger than no. 4 wire.
 - a) True
 - b) False

3. Voltage measurement must be made as close to the arc as possible to avoid voltage drop through the power circuit.
 - a) True
 - b) False

4. If more than one welder is working on a structure, DC machines must be connected to the same polarity.
 - a) True
 - b) False

5. Too low a wire feed roller pressure may result in wire slippage, leading to burn-back or a weld nozzle clogged spatter.
 - a) True
 - b) False

Answers - Guides

Module 5 - Power Sources for Welding

Guide 1

Q.1 b

Page 9, second paragraph

"a negative voltage is applied to the tungsten electrode"

Q.2 b

Page 10, What is Required to Start and Sustain an Arc?

"A high voltage with a low current capacity is used to create a spark."

Q. 3 a

Page 13, Formula

$$I = V/R \quad \frac{100}{200} = 0.5 \text{ amps}$$

Q. 4 a

Page 30, Rotating AC Generator

"The shaft is rotated perpendicular to a magnetic field"

Page 31, AC Alternator

"the magnetic field member is rotated inside the fixed armature windings"

Q. 5 a

Page 15, Resistors in Series

"A series circuit is a circuit with only a single path for current flow."

Guide 2

Q. 1 a

Page 46, Shielded Metal Arc Welding

"Steep slope minimizes the change in current from changes in arc length - constant current. This is a common preference when manually welding pipe joints."

Q. 2 c

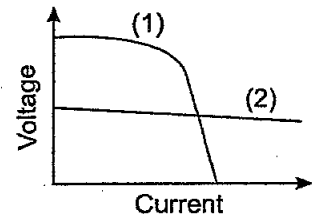
Page 44, Gas Tungsten Arc Welding

"A constant current power supply is used"

Q. 3 a

Page 46, 2nd paragraph

"Constant current power supplies can be used, both DC and AC"



Q. 4 b

Page 45, Gas Metal Arc Welding

"In the early development of gas metal arc welding (GMAW), constant current power sources were used."

Guide 3

Q. 1 a

Page 49, 1st paragraph

"Disadvantages of motor-generators are that they are bulky and heavy, have many moving parts which are prone to wear and require frequent maintenance, and are noisy."

Q. 2 b

Page 49, Welding Transformers

"A transformer (Figure 5.4) is an alternating current device used to convert high voltage line power to safer, useable low voltage levels"

Q. 3 a

Page 53, 1st paragraph

"A disadvantage of SCR Control is the very choppy output waveform,..."

"This rippled output is usually compensated for with banks of capacitors (Figure 5.10)."

Q. 4 b

Page 50, 1st paragraph

"the simplest method is to change the efficiency of "coupling" between primary and secondary."

Q. 5 c

Page 51, Silicon Controlled Rectifiers (SCR) - Thyristors

"The device still... must be switched on to allow current to flow."

Guide 4

Q. 1 a

Page 61, 2nd paragraph

"The steeper the slope,... and the less current will vary."

Q. 2 c

Page 67, Open Circuit Voltage - 1st paragraph

"This is the voltage that exists at its output terminals when the power supply is on..."

Q. 3 a

Page 67, Open Circuit Voltage - 2nd paragraph

"... to 80v, for safety reasons."

Q. 4 a

Page 68, 1st paragraph

"High short-circuit current tends to produce violent shorting reactions, ejecting metal in starts or metal transfer events, producing spatter."

Q. 5 a

Page 74, Output or Stabilizing Inductance - 2nd paragraph

"... helps in initiating or reinitiating of the arc."

Page 75, 1st paragraph

"...makes metal transfer smoother and reduces weld spatter."

Guide 5**Q. 1 d**

Page 77, Arc Starter Circuits - HF - 1st paragraph

"Initiating of a welding arc requires that electrical breakdown be achieved (see Section 4). This can be accomplished by the application of a sufficiently high voltage between the electrodes to exceed the sparking potential. Gas tungsten arc welding often employs a momentary application of high voltage via either a high frequency or impulse type voltage generator to achieve breakdown. High frequency, or "HF", systems create a continuously and rapidly fluctuating high voltage. This high voltage/low current either creates, or supports an ionized path through the gas media between electrodes. It is relatively easy to generate such a voltage with a spark gap generator circuit, and couple it to the welding electrode (Figure 7.1)."

Q. 2 a

Page 84, Required Current Range, DC, AC or AC/DC, Power Source Characteristics

- 2nd paragraph

"Inverter based power supplies for GTAW are now offering the ability to increase AC output frequency."

Q. 3 c

Page 77, Arc Starter Circuits - HF - 2nd paragraph

"In high frequency systems, incoming AC line voltage is stepped up to several thousand volts by a transformer."

Q. 4 b

Page 83, Primary Application

"The user must determine whether to select a machine which will cover a range of thickness and materials, and even processes, or whether the prime need for the machine is for a specific application."

Q. 5 b

Page 84, Required Current Range, DC, AC or AC/DC, Power Source Characteristics

- 2nd paragraph

"In welding, bigger is not necessarily better, ..."

Guide 6

Q. 1 b

Page 91, 1st paragraph

"Cable length should be minimized where possible."

Q. 2 b

Page 90, Table

"The recommended sizes in AWG for copper cable are given in the attached table:..."

Q. 3 a

Page 92, 3rd paragraph

"Voltage measurements must be made as close to the arc as possible..."

Q. 4 a

Page 89, Grounding - 5th paragraph

"If more than one welder is working on a structure, DC machines must be connected to the same polarity, ..."

Q. 5 a

Page 95, 1st paragraph

"... for example, too low a wire feed roller pressure may result in wire slippage, leading to burn-back or a weld nozzle clogged with spatter..."

Module 5 - Power Sources for Welding

Test

This test is designed to determine whether you are ready to attempt the formal examination.

Complete the ANSWER SHEET and compare the results with the test key. If you have a mark less than 70%, you are advised to re-study the material.

1. What is the purpose of an inverter?
 - a) Converts DC current to AC current of same frequency
 - b) Converts DC current to high frequency AC current
 - c) Converts AC current to DC current
2. When evaluating alternating current circuits, RMS values are used rather than peak values. Why?
 - a) the peaks are opposite to each other and therefore cancel out
 - b) RMS values allow AC circuits to be evaluated in an equivalent manner to DC circuits
 - c) average current is used not RMS when assessing AC circuit in a similar manner to DC circuits
3. Transformers designed for higher frequencies require much less iron core and windings than those designed for low frequencies.
 - a) True
 - b) False
4. The advantage of inverter based power sources is that the circuitry is more simplified than the conventional power source.
 - a) True
 - b) False
5. Which metal has the lowest resistivity?
 - a) aluminum
 - b) tungsten
 - c) copper
 - d) iron

6. Welding cable length should be kept minimum where possible. Because there is a voltage drop over the length of the cable, it must be compensated in order to maintain the correct welding voltage.
- a) True
 - b) False
7. In parallel electrical circuits, the voltage across each resistor is the same since each path is connected to the same voltage source. Select the correct statement.
- a) in each parallel path the resistance must be equalized
 - b) the current flowing in each parallel path must be the same as the voltage
 - c) the current flowing in each parallel path depends on the value of resistance in each path
8. Choose the correct statement to match the welding power characteristics:
- a) (1) is CV power source
 - b) (2) is CC power source
 - c) (1) is CC power source and (2) is CV power source
9. How much current will flow through a resistance of 50 ohms when 25 volts is applied?
- a) 2 amps
 - b) 0.5 amps
 - c) 5 amps
 - d) 0.2 amps
10. Inductance is a property of a circuit just as resistance is a property. Changing current flow through a circuit creates an "induced" magnetic field. What effect does the frequency of AC current have on the strength of the induced magnetic field?
- a) none
 - b) the higher the frequency, the weaker the induced magnetic field
 - c) the higher the frequency, the stronger the induced magnetic field

Gooderham Centre for Industrial Learning**Answer Sheet - Module 5**

Complete the "Answer Sheet" and compare the results with the "Test Key". If you have a pass mark less than 70%, you are advised to re-study the material.

Please circle only ONE letter corresponding to the answer you think is most correct.

QUESTION	A N S W E R S				
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e

The answer key below is provided for your use in the event that you wish to retest yourself.

QUESTION	A N S W E R S				
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e

Gooderham Centre for Industrial Learning**Test Key - Module 5**

Compare your answer sheet to this key.

QUESTION	A N S W E R S				
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e

