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The Use of Series Injection to Eliminate Voltage Distortion in Low and Medium Voltage Networks

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***Abstract* - Voltage distortion is seen as an interference on the nominal frequency, amplitude or shape of a voltage waveform. The most frequent voltage distortion is in the amplitude and shape of the voltage waveform. In this paper the voltage distortion in a rural distribution network is investigated and some of the problems experienced in this area are discussed. An increasingly popular form of rural electrification is that of Single Wire Earth Return (SWER) lines. This is a low cost method of electrifying small and remote communities fairly economically. This form of distribution is however prone to voltage distortion due to its high regulation. The question is posed as to how the voltage quality supplied to these users can be economically controlled. Not only can this be a solution to the voltage quality problem, but it can possibly increase the load capacity per line in cases where the capacity is limited by voltage regulation. A closer look is taken at the use of series injection to supply the additional voltage required to compensate for voltage regulation. An experimental setup is made to evaluate the argument in a practical manner. The experiment also served to provide confirmation of the required capacity of the series voltage source used for the series injection.**

I. Introduction

In Single Wire Earth Return (SWER) power lines the earth provides one of the conduction paths and buried electrodes at the source and load are used connect the conductors to the earth. SWER lines are used mainly where the power requirements are very low and the rural population very distributed. This solution is provided where the return on investment period is not necessarily very short and low cost solutions to electrification need to be implemented. Due to the distance covered by these lines and the relatively low voltages and high resistance conductors, voltage drops across these lines are quite large. This leads to voltage compensation problems and because of the lack of standard compensating equipment alternative methods for regulating voltage must be explored.

The subject of voltage distortion has been widely discussed and solutions for the problems regarding the subject frequently published. In this investigation two categories of distortion are differentiated, both primarily due to the high network impedance.

a) momentary dips in the supply due to fault conditions.
b) Steady state under voltage conditions due to large loads.

A. Momentary disturbances

Due to the of the lack of the second physical wire and the greater distance between the two conducting media the probability of inter-conductor faults causing voltage distortion is reduced compared to a conventional two wire distribution system. Low voltage conditions do however exist and Figure 1 shows the distribution of these low voltage conditions as supplied by the South African power generation company ESKOM [1].

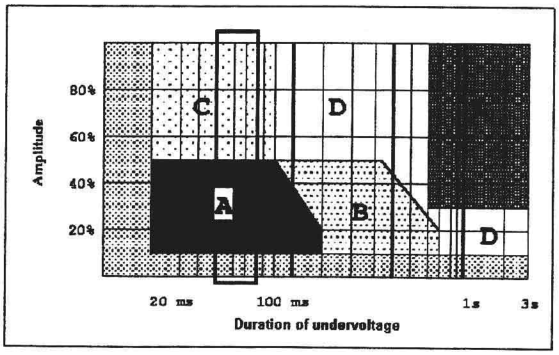

Figure 1. Low voltage conditions window

Table 1 lists momentary disturbances as recorded over a large time and it can also be seen that low voltage conditions are by far the greatest contributing factor to voltage distortion and if it could be eliminated the greatest part of the distortion problem can be solved. From figure 1 it can be seen that it is not necessarily every low voltage

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condition that can be effectively eliminated. According to [1] Areas A and B are mainly due to the long distance between user and fault condition. These are also the areas that are the easiest to compensate for and will be addressed in this study.

TABLE 1
OCCURRENCE OF MOMENTARY VOLTAGE DISTORTION PHENOMENA

Distortion	% Occurrence
Dips	87
Spikes	7.4
Power failures	4.7
Surge	0.7

B. Steady state under voltage

Due to the large line impedance the line regulation is very large. With a high load connected, under voltage conditions are intolerable. This limits the capacity of these types of line. The most obvious solution to this problem is through the use of a tap changer However due to daily fluctuations in network load and hence network load, an off-line tap changer can not be used. On line tap changers can be used to compensate at more regular intervals. These tap changers however suffer from several disadvantages. The most prominent disadvantage in this application is that of the required maintenance. Non-ideal contact phenomena and the repeated connecting and disconnecting of high voltages cause electrodes to arc and form impurities in the transformer oil. Regular maintenance is therefore required. In a rural setting with a widely distributed network the required maintenance program has proven to be very difficult to implement.

The high maintenance of on load tap changers can be offset to some extent through the use of solid state tap changers implemented with thyristors. This can solve the steady state regulation problem, but momentary disturbances are still an issue.

With the use of high power semiconductor switches, series voltage injection by switch mode converters becomes a viable option at power levels required in low and medium voltage networks. This type of compensation, although more complex in nature, has significant advantages such as improved dynamic response. The faster dynamics of the system can however lead to network stability problems which need to be addressed.

II. APPLICATION

A case study was performed on a typical SWER distribution network in order to determine the regulation. The network in question is installed at Sabie Sands in South Africa. The layout of the network is shown in Figure 2. The specifications for this line are given in Table 2. The characteristics of each type of conductor is listed in table 3.

The first section of the SWER distribution network, between point 1 and 2 in figure 2, is done with the more expensive Fox conductor to allow the minimum impedance and therefore the lowest voltage drop since it carries the load current from all the users. At the connection point 2 (the first customer) the line is replaced with more economical Magpie conductor. The total load current starts to decrease as we move closer to the end, point 3 of the conductor. An analysis of the voltage drops based on this configuration is done and the results shown in figure 3.

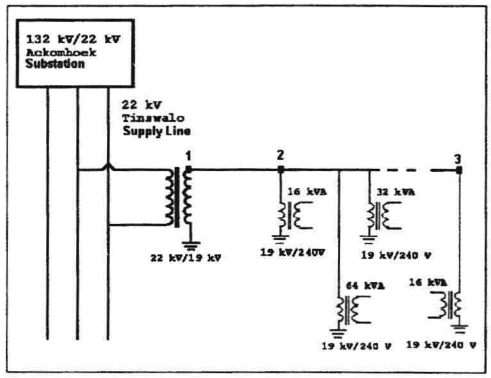

Figure 2. Layout for SWER distribution Network in Sabie Sands

TABLE 2
SWER LINE SPECIFICATIONS AT SABIE SANDS

Power rating	360 kVA at 19kV
Conductors	Point 1 to point 2 -Fox Point 2 to point 3 -Magpie
Loads	11x 16 kVA 2x 32 kVA 1x 64 kVA

TABLE 3
CHARACTERISTICS OF CONDUCTORS

Conductor	Impedance	Cost/km for 0.5 MVA load
Fox	0.86 + j0.91	$ 1,400.76
Magpie	3 + j0.87	$ 863.31

The voltage drop at the first customer is 243V increasing to approximately 4.5kV at the end customer.

At a line voltage of 19 kV this amounts to a regulation value of 24%. This regulation is well beyond the acceptable bounds. Although this is a worst case scenario, measures need to be taken to address this problem.

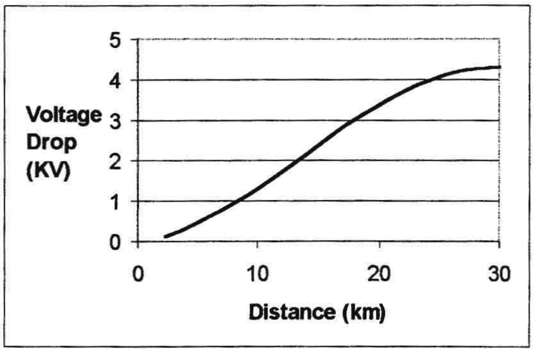

Figure 3. Voltage drop distribution across SWER line

III. Solutions

By making use of parallel injection the current in the SWER can be increased, overcoming the effects of low voltage conditions [2]. This approach has already been evaluated and need not be repeated

A. Series injection

By making use of series injection the voltage at each individual consumer needs to be controlled to allow a non-varying voltage supply. This will require the installation of a PWM converter, in this case, at each distribution transformer of a consumer connected to the SWER distribution network. This is caused by the unknown amount of voltage sag at a given point in the system which needs to be compensated. Because of the increase in power required to compensate for losses it may be required to add a compensating device to the main supply of the SWER line as well, to add additional power as required.

B. PWM inverter as series voltage source

As mentioned previously the voltage source to be used to inject voltage in series with the load voltage is a PWM voltage source inverter. This inverter will be supplied from an additional winding on the secondary of the distribution transformer. The voltage will be injected in series with the load. To minimise the amount of components and to reduce cost the leakage reactance of the injection transformer is used as the inductance to form the output filter for the PWM inverter. This configuration requires the filter capacitor to be transformed to the secondary side of the injection transformer to maintain the inductive input to the. filter. The complete configuration can be seen in figure 4.

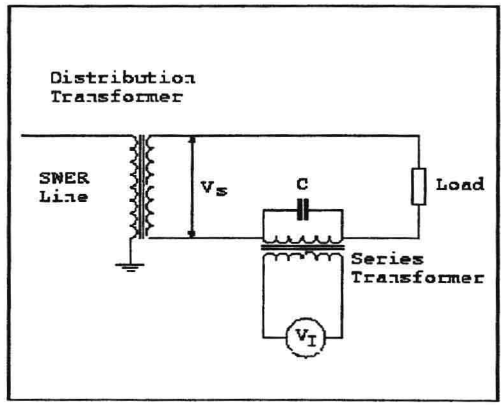

Figure 4. Proposed compensating scheme

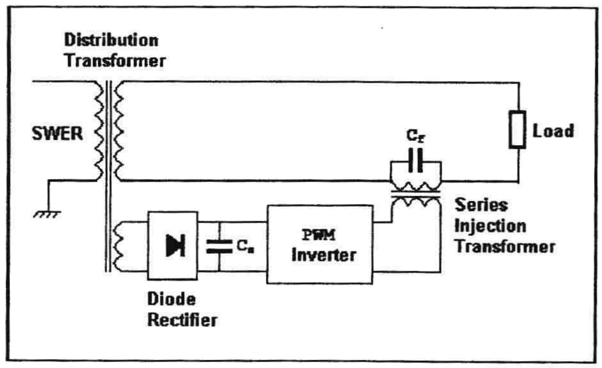

Figure 5 Line diagram of proposed compensation network

IV. System analysis

In order to obtain a controllable parameter in the SWER power distribution system it is necessary to define what the system consists of. For the purpose of compensating for a low voltage condition at the connecting point of a single user to the power network the equivalent circuit shown in Figure 5 will be used. It consists of an additional winding on the secondary of the distribution transformer that supplies the additional power to increase the voltage to the required level.

For a 16 kVA load at 220 V a voltage drop of 10% would require about 1.6 kVA to compensate for the voltage drop at full current. This power requirement can be satisfied by using a PWM Voltage Source Inverter (VSI). To analyze the system the circuit diagram of Figure 6 is used. In order to write down the voltage loop equations the voltage sources and current sources are identified and the analysis done for the fundamental frequency only. This is because for voltage-dip compensation the amplitude of the fundamental is the only voltage component considered.

For this analysis the distribution transformer is labeled V_S and the PWM VSI as V_I. In the circuit V_I acts as a short circuit path for harmonics and therefore harmonic currents generated by the load circulate through the voltage source. The secondary winding of the injection transformer, as seen from the network side, is seen as a short circuit and the only contribution to the voltage drop is made by the parasitic elements and they are included in the analysis. Transformer core-loss is small compared to the other parasitic elements and disregarded for this analysis leaving the copper loss, R, and the leakage reactance, X_L. Sources are identified to complete the circuit and their behavior modeled by substituting elements with similar behavior thus the distribution transformer becomes voltage source V_S, and the load, because it injects current harmonics in the system, becomes a current source. Z represents the impedance existing in the distribution network.

Summation of voltages around a loop for figure 6

$$V_S + IZ + V_{XC} + V_T = 0$$

provides the following loop equation:

$$-V_T = V_S + IZ + I_C X_C$$

Making use of the superposition principle the current through the capacitor is determined as the sum of the currents in either loop :

$$I_C = I_{C1} + I_{C2} = \frac{V_I}{Z_T} + \frac{I\sqrt{R^2 + X_L^2}}{Z_T}$$

Where :

$$Z_T = \sqrt{R^2 + (X_L - X_c)^2}$$

Substituting the values back into the equation without simplifying gives the relationship between the variable and fixed components in the distribution circuit :

$$-V_T = V_S + IZ + \frac{X_C V_I}{Z_T} + \frac{I X_C \sqrt{R^2 + X_L^2}}{Z_T}$$

In this equation Z, Z_T, X_C, V_T, R, X_L are constants and thus not controllable. The load current I is determined by the load and is variable dependant on the user. V_S is a fixed value subject to voltage variations and also the voltage to be compensated by series injection. This leaves only V_I as controllable parameter to keep the output V_T constant.

This analysis serves only to confirm what was intuitively felt that the voltage across the load can be kept constant by adding a controllable voltage source in series with the supply.

5. Implementation

This voltage compensation strategy will need to be implemented at each point on the SWER line where a user is connected. This is due to the connection of all users to a single line as was shown in figure 2.

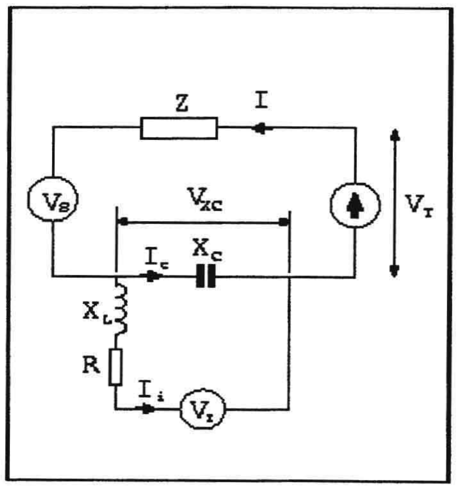

Figure 6 Simplified line diagram of proposed compensation network

Due to the duplication of the strategy as proposed, it could easily be seen as a costly process. The required capacity for compensating at 10 % voltage drop on various loads gives the results indicated in table 4.

TABLE 4
POWER REQUIRED TO COMPENSATE VOLTAGE DROP AT FULL LOAD

Distribution Transformer capacity	Nominal line voltage	Voltage drop	Power Required
16 kVA	220 V	10 %	1.6 kVA
32 kVA	220 V	10 %	3.2 kVA
64 kVA	220 V	10 %	6.4 kVA

Due to the low power requirement the cost involved in this solution is justified. Making use of this concept it is possible to increase, the amount of users connected to a single SWER feeder. By increasing the utilization per feeder the cost per consumer for distribution hardware can be reduced.

6. IMPLEMENTATION

To evaluate the effectiveness of this proposed compensating technology an experimental setup was made and a single user compensation was done. The experiment consisted using the same configuration as in figure 4 to create an experimental setup with the exception that SWER line was a single phase network with an artificially high impedance.

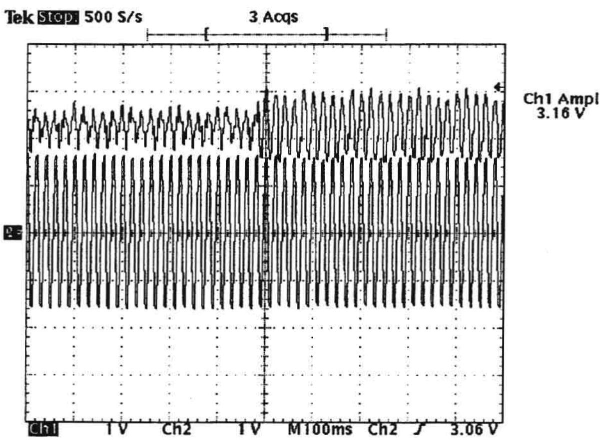

Figure 7. Step load compensation

A step change was introduced into the network by dropping the voltage by 20 % of its amplitude. This step can be seen in the control signal in figure 7 – the top small signal. It can clearly be seen that the output voltage is still of the correct amplitude and performs as is expected by maintaining its nominal value.

The proposed system of series voltage injection is superior to the electronic tap-changing schemes because the output voltage is not limited to discreet steps. A continuous voltage range can be obtained with the use of a PWM inverter in series. This configuration can therefore also be a substitute for tap changers where load requirements can be met by semiconductors.

An additional advantage to the proposed topology of using a PWM inverter as alternative to tap changers has is the ability to compensate for voltage harmonics. A sinusoidal reference voltage is already generated and due to the result of the comparison of the signals of the reference and the network voltage a resultant voltage is generated that could cancel voltage harmonics upon injection. This cancellation is however only obtainable provided the inverter has sufficient bandwidth.

7. CONCLUSION

Making use of existing technology a low cost and effective solution to voltage distortion problems in a SWER system can be provided. This proposed compensating strategy has the added advantage that it can be implemented as required by the customer. It is a relatively low cost and easy solution to the problem.

In terms of power quality supplied to the customer the proposal of using series injection to compensate for voltage dips is quite successful and the use thereof in SWER lines is quite viable. Implementation of this proposed topology and its protection against lightning and network faults are still issues to be addressed in the final step in proving this solution to the SWER power distribution technology in a practical system.

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Power Quality Considerations for CNC Machines : GROUNDING

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Abstract **- Computer Numerical Control (CNC) machines are used to shape metal parts by milling, boring, cutting, drilling, and grinding. A CNC machine generally consists of a computer-controlled servo-amplifier, servo-motors, spindle motor, and various tooling. The machine can be programmed to shape a part by use of a front control panel. More sophisticated models allow a CAD drawing to be uploaded to the machine. The electronic components within a CNC machine are particularly sensitive to the grounding techniques used in the electrical supply to the machine. Malfunction, degradation, and damage to the electronics can often be traced to problems with the grounding system. Production downtime, product loss, and expensive repair bills result. With the wide-spread use of CNC machines across the world, these problems have become a significant financial concern to many CNC machine users and their electric utility companies.**

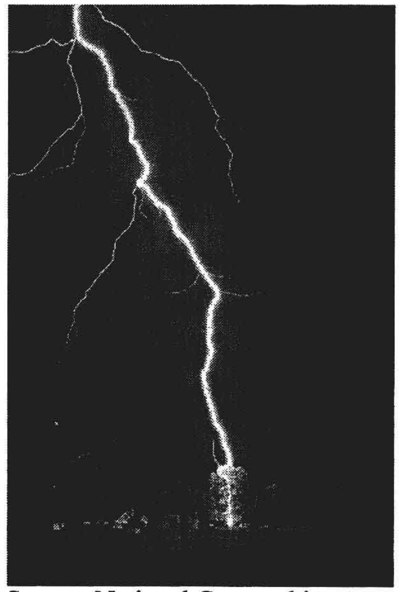
This paper begins with a brief explanation of the fundamentals of service and equipment grounding. The basic design of CNC machines is also explained. Based on a survey of several CNC machine representatives, the paper will explore the common grounding techniques recommended by many CNC machine tool builders with particular emphasis on the ground rod problem. In addition, several actual case studies that support the ground rod problem will be described. Finally, a recommended powering and grounding practice is presented to help eliminate power quality related operating problems with CNC machines while maintaining the safety requirements of electrical codes.

Index Terms **– Computer Numerical Control, CNC, power system grounding, ground rod problem, damage.**

I. BUILDING SERVICE GROUNDING

The logical place to begin discussions on grounding is at the electrical utility service entrance. Most machine shops are supplied with a three-phase service classified as a "four-wire grounded" or a "three-wire ungrounded" system. Common voltages of grounded systems are 208Y/120 V and 480Y/277V, and common ungrounded system voltages are 240V delta and 480V delta. Both grounded and ungrounded electrical systems are required to be connected to earth via the building grounding electrode system. This practice is referred to as ***grounding*** or ***earthing*** for safety[1].

In grounded electrical systems, one of the current-carrying conductors (typically the neutral) is solidly grounded to the building grounding electrode system, providing a stable reference to the surroundings



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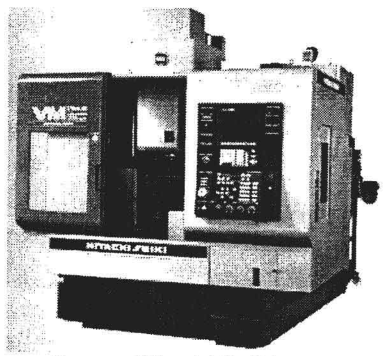

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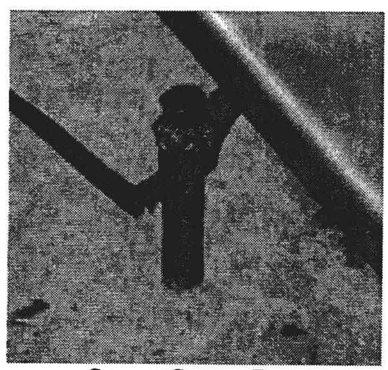

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(earth). The neutral is also connected to the building's equipment grounding system through the main bonding jumper, which facilitates the operation of over-current protection devices (fuses and circuit breakers), during a ground fault. All conductive (metal) enclosures of the electrical system are also bonded together and to the power system grounding point to keep metal parts at ground potential preventing shock hazards. Fig. 1. shows a typical solidly-grounded building electrical system[1].

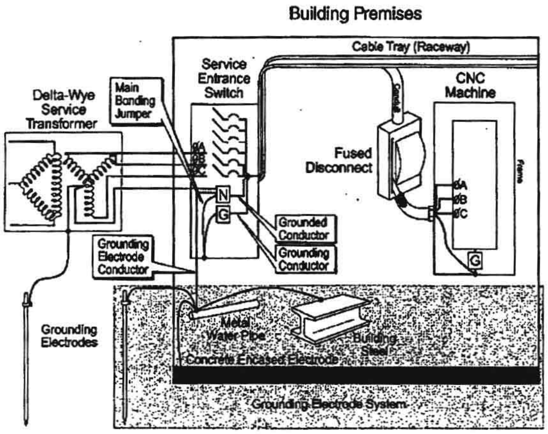

Fig. 1. Typical grounded building service and grounding Electrode System

In an ungrounded electrical system, no circuit conductors are intentionally connected to ground. The advantage of an ungrounded electrical system is that the system can continue to operate with a single ground fault, avoiding production delays. Disadvantages of an ungrounded system are undetected ground faults and uncontrolled voltage build-ups between the insulated electrical power system conductors and various exposed metal parts or equipment enclosures. For many sensitive electronic devices these uncontrolled voltage potentials can be damaging. Hence, unless specified by the manufacturer a CNC machine may not be suited for powering from an ungrounded electrical system. For ungrounded systems a ground fault detector should be used to alert qualified personnel that an inadvertent ground fault has occurred. Fig. 2. shows a typical ungrounded electrical system. Note that exposed metal parts are still bonded to the building grounding electrode system[1].

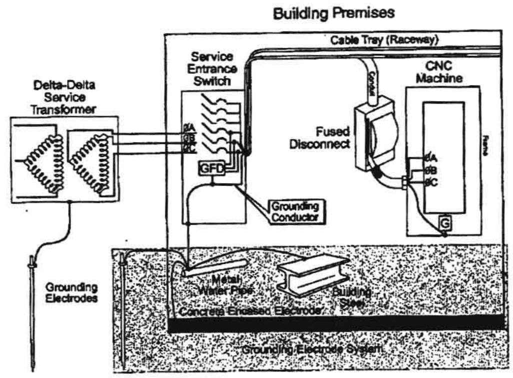

Fig. 2. Ungrounded building service and grounding electrode system

Both grounded and ungrounded building electrical services require a grounding electrode conductor to reference the electrical power system to the building grounding electrode system. The grounding electrode system consists of all available earth electrodes, including building steel, metal water pipes, buried ground rings, and ground rods. The intent of the grounding electrode conductor and grounding electrode system is to provide a low impedance path to earth for lightning surge current and to reference the building electrical system to its surroundings. This minimizes voltage differences between exposed metal parts of the power system including connected equipment and the surrounding parts of the building thus reducing the hazard of electrical shock[1].

II. CNC EQUIPMENT GROUNDING

Besides the grounding electrode system, another fundamental of safety grounding is the equipment ground. The fundamental purpose of equipment grounding is to provide equipment and personnel safety, and the secondary purpose of equipment grounding is to enhance equipment performance by providing a reference for the electronic components. Equipment grounding intends to ***effectively ground*** all non-current-carrying metal parts of the electrical system, including equipment enclosures and raceways.

The proper combination of equipment and system grounding should ensure that a ground fault anywhere in the system would not pose a shock hazard to personnel. In case of a ground fault with a solidly grounded electrical system, the low-impedance equipment-grounding path allows the fault current to flow back to the power source. With sufficient ground fault current, the over-current protection device will trip quickly and clear the ground fault.

According to the NEC, metal raceways, such as conduit, are acceptable means of equipment grounding. Quite often though, especially with sensitive electronic equipment, a conductor is also used to supplement the conduit and further ensure effective grounding. This is usually done because conduit connections can become loose or corroded over time. To maintain a low impedance ground path, the equipment-grounding conductor must always be routed in the same conduit or raceway with its associated power conductors[1].

III. CNC MACHINE COMPONENTS AND SUSCEPTIBILITIES

A CNC machine is typically composed of a controller with appropriate computer program describing the desired part, servo-amplifiers and positioning motors to control relative movement of the part and shaping tools, and spindle motors that actually work to shape the parts. Positioning of the part or the tooling is typically accomplished by turning a screw mechanism and moving a nut in one or more axes. Some machines have five axes, 3-dimensions plus a horizontal and a vertical axis of rotation. See Fig. 3. illustration of a typical CNC machine and controller with 2-dimensions and a horizontal axis of rotation[2].

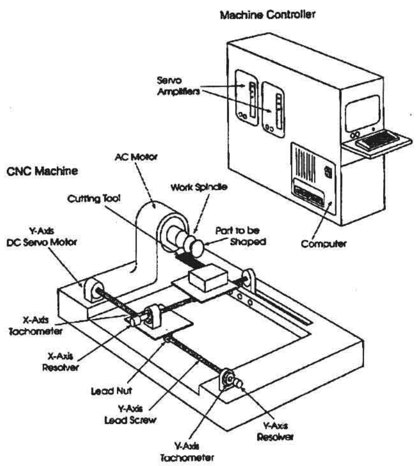

Fig. 3. Illustration of a typical CNC machine and controller

The CNC machine controller contains a computer to provide overall control of the machine. It usually monitors the machined part's position by feedback from the resolvers or encoders to update the program. Movement is accomplished by positioning motors with velocity-based feedback from tachometers to the computer. The speed of the spindle motor is also variable using an adjustable speed drive with either computer or manual control[2].

The onboard computer can be programmed through the unit's front panel or through a communication port where the required data from a CAD drawing program can be downloaded from a remote computer. The CNC machine microprocessor then executes the program, setting up the machine sequence, determining the desired speed and position for machining, etc. When there is physical separation between the CNC machine and its electronic control, certain functions may be sensitive to the machine powering and grounding techniques[2].

Electrically, the AC power is usually converted to several levels of DC for servo systems and computer logic. Fig. 4. shows the AC power sources, functional blocks and interconnections for a typical CNC machine. Also the data link to another area of the factory is likely to have a signal reference ground in that area of the factory's power system. These different reference ground points may increase the CNC machine's sensitivity to power disturbances.

Today's electronically controlled CNC machines require a common signal reference ground for logical circuits to operate reliably. The term, signal reference describes the zero-voltage level used by digital logic circuits. For example, five volts DC above signal reference indicates a logic level "1" and zero volts DC indicates a logic level "0." This signal reference is typically the common of the computer logic power supply, which is connected to the machine's ground plate. The ground plate is bonded to the machine's enclosure, equipment grounding conductor or conduit and, subsequently, to the building grounding electrode system. So the equipment ground establishes the local signal reference both within the CNC machine and for any remotely connected devices.

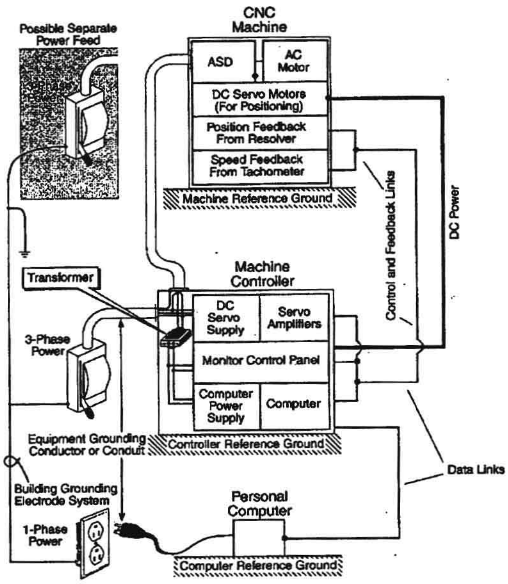

Fig. 4. AC power sources functional blocks and interconnections for a typical CNC Machine

CNC machine upsets that are related to grounding and ground reference are usually attributed to noise or stray currents that find ways into logic circuits. Susceptibility of CNC machines to different sources of noise and stray currents will depend on how the machine is designed and installed. Grounding, bonding, and shielding also play a role in its immunity. For example, certain types of communication circuits are more susceptible to high frequency noise; others are more susceptible to stray ground currents, whereas others (fiber optic) are not susceptible to either.

IV. NOISE SOURCES AND COUPLING MODES

Much of the focus of special grounding recommendations for electronic equipment is based on reducing electrical noise, or any unwanted signal that may affect logic circuits or signal. Sources of electrical noise may be nearby transmitters—both intentional and unintentional—like electric welding arcs or chattering relay contacts. Also, lightning or switching surges may capacitively-couple noise-voltages into sensitive control circuits. A common wiring-related noise source is simply the normal electric currents that inductively couple noise currents into control wires if control and power wiring are run in the same raceway or run close to each other inside the CNC machine. Internal to the CNC machine, contactors, relays, solenoids, and motor drives are a large source of noise and transients, which may also affect the logic circuits[3]. CNC machines that are contained in a single cabinet with good bonding, grounding and shielding should be relatively immune to noise. However CNC machines with remote controllers or data links may be quite susceptible. In these machines two forms of this ground-related noise should be considered. See figure 4. One form is the noise appearing on the input power conductors relative to the equipment ground (typically the enclosure or chassis ground). The other is the noise or difference in potential that appears between the grounds of interconnected equipment. When trying to avoid electrical noise, distancing from the source of noise is usually a great help. Some grounding practices can also help to control the noise relative to ground, but watch out for myths about ground noise problems. Remember that electrical noise or unwanted signals will follow the fundamental principles of electricity, i.e. currents flow only when there is a difference in potential and a completed circuit, and they follow paths of least resistance (reactive impedance in the case of high-frequency signals)[3].

V. THE GROUND ROD PROBLEM

To combat the problem of unwanted electrical noise on the equipment grounding system, many CNC machine tool builders require or recommend that a ground rod be driven into the earth at each CNC machine and connected to the CNC machine's frame via the ground plate. Fig. 5. shows a typical installation. Some CNC machine tool builders will void the warranty if the ground rod is disconnected. Many CNC machine tool builders feel that the building's equipment grounding system is "noisy" because of nearby equipment in the facility such as welders, wire EDM machines, and motor drives. The supposed purpose of the ground rod is to carry away or eliminate this unwanted electrical noise from the CNC machine's data signals. Apparently, these CNC machine tool builders believe the ground rod provides a low impedance path for this noise to flow. The recommended impedance of this path ranges from no more than 5 ohms to no more than 100 ohms. These CNC machine tool builders feel that the building's equipment grounding system does not provide a reliable, low impedance path to earth. CNC machine tool builders that have recommended installing a ground rod to eliminate unexplained operating problems report that the problems go away more often than not. In addition, some feel that the ground rod provides lightning protection. On the contrary, other CNC machine tool builders do not recommend a ground rod at the CNC machine because of lightning problems[4][5].

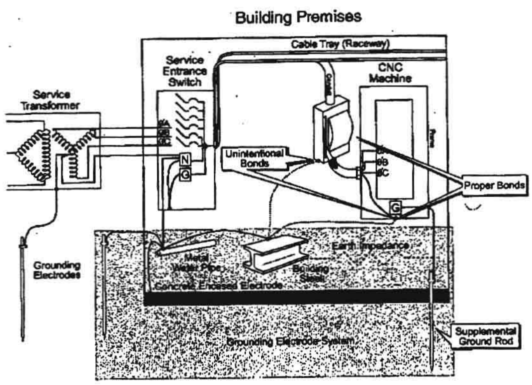

Fig. 5. Supplemental ground rod properly installed may invite stray ground currents

Obviously, CNC machine tool builders and service technicians recommend many confusing and conflicting grounding techniques. Quite often, these techniques, implemented to help correct operating problems believed to be caused by electrical noise, can actually lead to more severe problems such as damage during lightning storms. Of particular concern is the practice of driving a ground rod directly at the CNC machine and connecting that ground rod to the CNC machine's ground plate. The presence of this ground rod creates a ground loop with the earth. The ground loop is a conductive path for current to flow between the grounding electrode system at the main service switch through the conduit/equipment grounding conductor to the CNC machine's ground plate, then through the ground rod at the CNC machine and back to the grounding electrode system through the earth. Current will flow in this path when a voltage difference develops between the two earth connections. Current flowing through the earth, such as that during a lightning strike or utility ground fault, can create an extremely large voltage difference.

The presence of the ground rod also creates a path to earth, which allows lightning current and utility fault current to travel on the conduit/equipment grounding conductor. When lightning strikes a facility, the lightning current flows into the earth at the main service switch (grounding electrode system) and also travels along the conduit/equipment grounding conductor through the CNC machine and into the ground rod driven in the earth[4].

Fig. 6. shows how utility fault current flowing through the earth can flow up the CNC machine's ground rod, travels along the conduit/equipment grounding conductor, onto the utility neutral and back to the source (the utility substation). The presence of these large currents can result in malfunction, degradation, and damage to the electronic components within the CNC machine[4].

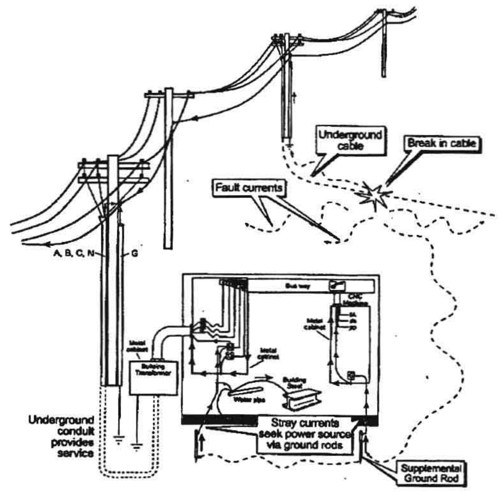

Fig. 6. Power system ground fault causes a high current via the supplemental ground rod through a CNC machine

Drawing a comparison with other electronic equipment, like computers, electronic motor drives, programmable logic controllers, none subscribe to such a local grounding practice. The analogy would be to drive a separate ground rod in the office, and connect it to the logic ground inside your personal computer. Such a practice is not recommended by IEEE Standards such as STD-1100 on powering and grounding sensitive electronic equipment. Instead, a single-point ground, from individual electronic cabinets, is individually bonded to a local ground grid. Since specific practices for CNC machines are not provided by any existing codes or standards an initiative is currently underway to bring end-users, CNC machine manufactures, consultants and utilities together to work out and publish a best powering and grounding practice for these very important tools of industry.