Product Data

Class 8800

Subject: THE EFFECTS OF ADJUSTABLE FREQUENCY CONTROLLERS ON THE AC LINE

Abstract:

Much information has been written over the past few years concerning the adverse effects that solid state motor controllers have on the incoming power line. Knowledge of potential problems is normally limited to those persons who have experienced difficulties and have been forced to take corrective action. The intent of this paper is to provide a broad introduction to the concept of how adjustable frequency controllers affect the ac line and to provide references for interested parties who wish to dig deeper into this relatively complex subject.

Introduction

Adjustable frequency controllers are devices which change fixed voltage and frequency to adjustable voltage and frequency for application to ac motors in order to change operating speed. Two stages of power conversion are involved as shown in the block diagram Figure 1.

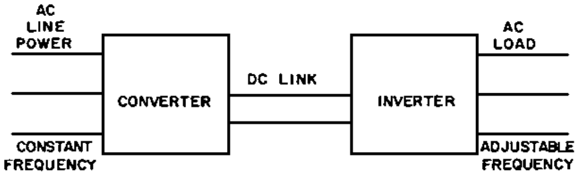


FIGURE 1

ADJUSTABLE FREQUENCY CONTROLLER BLOCK DIAGRAM

The converter stage changes fixed voltage ac to either fixed or adjustable voltage dc. The inverter stage changes the fixed or adjustable voltage dc back to ac at the desired frequency and voltage. An important basic concept is that the voltage to frequency ratio, commonly called volts per hertz ratio, remain relatively constant over the operating speed range in order to maximize torque and prevent excessive motor current. This requirement dictates which of converter-inverter types can be used together. Of the three different types of inverters two require variable dc voltage input. These are the variable voltage source inverter commonly called six-step, and the current source inverter. Only the Pulse Width Modulated (PWM) inverter can operate with a fixed supply of dc voltage.

The converter stage of an adjustable frequency controller is the primary determining factor in what effects the controller has on the ac line. The three types of converters are described below.

The diode bridge rectifier shown in Figure 2 is the simplest converter. The six power diodes form a three phase, full-wave bridge which changes line ac voltage to a fixed dc voltage. The diode bridge has no variable voltage capability and is therefore limited to use with PWM inverters.

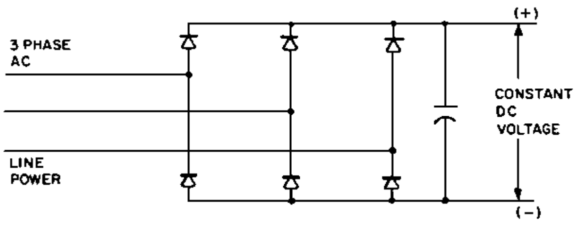
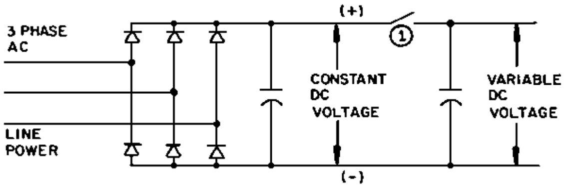


FIGURE 2

RECTIFIER (DIODE) CONVERTER

By adding a semiconductor switch such as a transistor or SCR to a diode bridge rectifier a second type of converter called a diode bridge with a dc chopper is formed. The power circuit is shown in Figure 3. The function of the chopper is to change the constant dc volts output of the diode bridge into a variable dc voltage.



① SOLID STATE SWITCH (TRANSISTOR, GTO, SCR)

FIGURE 3

RECTIFIER WITH DC CHOPPER CONVERTER

The third type of converter replaces the six power diodes with silicon controlled rectifiers (SCRs) as shown in Figure 4.

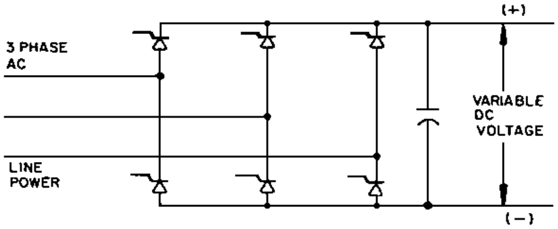


FIGURE 4

SILICON CONTROLLED RECTIFIER CONVERTER

Variable dc voltage is produced by controlling the point in the incoming ac voltage waveform at which gating pulses are applied to the SCRs.

The effects that the converter stage (commonly called front end) of an adjustable frequency controller have on the ac line normally fall into three categories. These are voltage transients or line notching, harmonics and power factor. Of the three types of front ends, all cause harmonics and all effect the total power factor to some extent. Only the SCR front end causes significant line notching or has significant effect on the displacement power factor. The remainder of this paper will look at each of the effects in more detail.

Voltage Transients (Line Notching):

In order to understand how line notching occurs, it is necessary to have an understanding of the operation of a converter. Figure 5A shows a typical three phase full, wave converter. The power switching devices are shown as diodes, but SCRs could also be used. The numbers in the power device symbols indicate the order of conduction with a three phase input as shown in Figure 5B.

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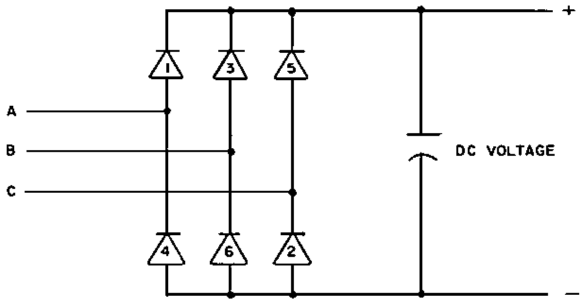


FIGURE 5A
AC — DC CONVERTER

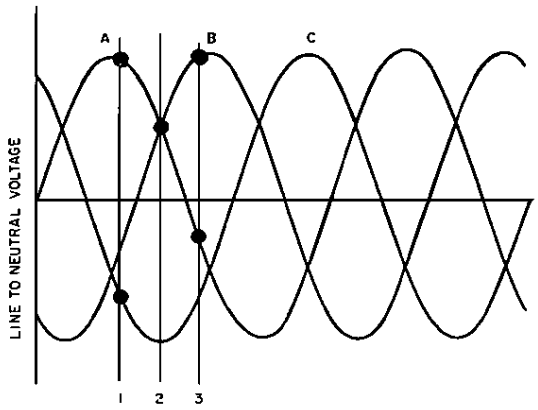


FIGURE 5B
THREE PHASE AC LINE VOLTAGE

Following the three phase input voltages starting just past the positive peak of the phase A voltage (point No. 1) we see that at this instant in time phase A is more positive than any of the other phase voltages and phase C is more negative. This means that current will flow from phase A through device number 1, through the load and back to phase C through device number 2. Moving to point 2 where the phase A, phase B voltages are equal, current flow is beginning to transfer from device number 1 to device number 3. During this brief period of time when both device number 1 and device number 3 are conducting, a line-to-line short circuit exists between phase A and phase B. The current which flows during this brief short circuit is limited by the short circuit current capability of the ac line and the difference in voltage between A and B phases. If a significant difference exists between the phase A and phase B voltages, a notch is produced in the phase-to-phase voltage waveform. Since there are six power switching devices, six notches are produced for each complete cycle of the three phase voltage.

When diodes are used in the adjustable frequency controller front end, the line notching is insignificant because there is very little difference in the phase voltages at the time the current flow is transferring. If, however, SCRs are used to provide variable dc voltage, the SCR turn on might be delayed past the normal transfer point. This condition is illustrated at point 3 in Figure 5B. Notice that there is now a large difference between the phase A and phase B voltages. This results in a more severe notch. Theoretical line notching for a converter using SCRs to produce a variable dc voltage is illustrated in Figure 6.

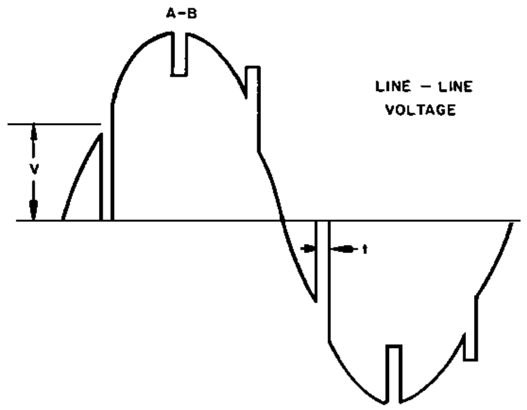


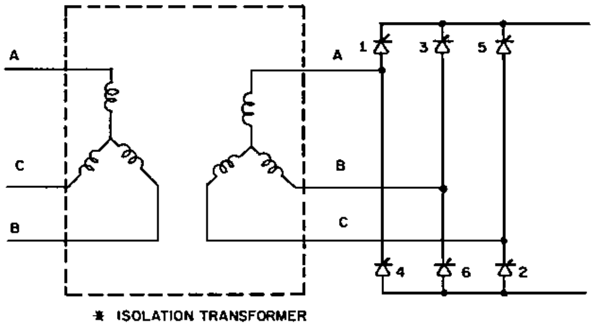
FIGURE 6
LINE NOTCHING DUE TO SCRs THREE PHASE FULL WAVE BRIDGE

IEEE 519-1981[1] describes the effect of the notch as a function of the notch area which is defined as the notch depth (expressed in volts) times the notch width (expressed in microseconds). The units are therefore volt-microseconds. Increasing notch area yields increasing effects.

Voltage transients caused by operation of an SCR converter can result in problems as listed below.

1. Misoperation of sensitive electronic equipment
    - Computers
    - Programmable Controllers
    - Other Adjustable Speed Controllers
2. Interfere with communication equipment
3. Severe cases can cause light flicker

The user can take steps to eliminate or minimize the effect of voltage transients. These include 1) using adjustable frequency controllers with a diode or diode/chopper front end or 2) if adjustable frequency controllers with SCR front ends are used, install an isolation transformer or line reactors ahead of the controller as shown in Figure 7. The isolation transformer or line reactors will minimize the line notching on the line side of the transformer by introducing impedance between the ac line and the converter bridge. Voltage notching will then be proportional to the ratio of the available short circuit capacity of the converter side of the isolation transformer to the available short-circuit capacity of the ac line.



* NOTE: A WYE CONNECTION IS SHOWN, BUT OTHER CONNECTIONS ARE POSSIBLE

FIGURE 7
ISOLATION TRANSFORMER ADDITION TO MINIMIZE LINE NOTCHING

Harmonics:

All adjustable speed controllers which employ solid state power devices cause harmonic currents in the ac line due to the distorted currents produced. A harmonic is defined as a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. This is illustrated in Figure 8. Assuming the fundamental is 60 Hertz, the 5th harmonic would be 5 times 60 Hertz or 300 Hertz.

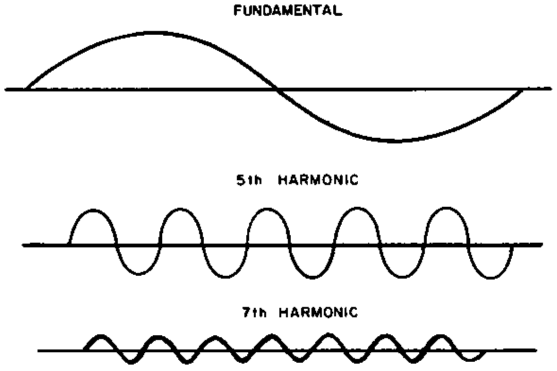


FIGURE 8

FUNDAMENTAL WITH 5th & 7th HARMONIC

As previously mentioned, harmonics result from distorted ac line currents. The most common current waveforms encountered are shown in Fig. 9. Figure 9A shows the square wave line currents produced by an adjustable frequency controller front end operating as a current source to the DC link and Figure 9B shows the typical shape of the ac line currents provided by an adjustable frequency controller front end operating as a voltage source to the DC link. The waveforms of Fig. 9A are typically encountered on certain types of SCR front ends while the waveforms of Fig. 9B are typically encountered on bridge rectifier front ends.

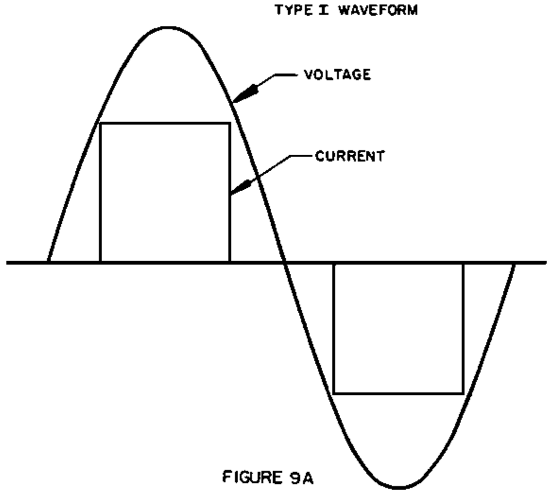


FIGURE 9A

AC LINE CURRENT WITH INVERTERS

For the waveform of Fig. 9A, the harmonics present in a system and the theoretical magnitude of the harmonics can be calculated using simple formulas. The following formula calculates the harmonics which will theoretically be present on a balanced three phase system.

$$h = Kg \pm 1 \qquad (1)$$

Where: h = the harmonic order

k = any integer 1, 2, 3, ...

g = the pulse number of the circuit (i.e., the number of power switching devices)

Using this formula for a six pulse converter it can be seen that the first harmonic present would be the fifth. Also present would be the seventh, eleventh, thirteenth, seventeenth, nineteenth, etc. Note that the third harmonic and multiples of the third harmonic are not present for a balanced three-phase system. Also note that even harmonics are not present.

The magnitude of the harmonic currents of a six pulse converter waveform of Fig. 9A can be calculated by the following formula.

$$I_h = I_1/h \qquad (2)$$

Where: I_h = the harmonic current magnitude

I_1 = the fundamental current magnitude (1 per unit, p.u.)

h = the harmonic order

Using this formula it can be seen that the magnitude of a particular harmonic is the inverse of that harmonic. In other words, the magnitude of the fifth harmonic is 1/5 of the fundamental, the magnitude of the seventh harmonic is 1/7 of the fundamental, etc. This data is summarized graphically in Figure 10.

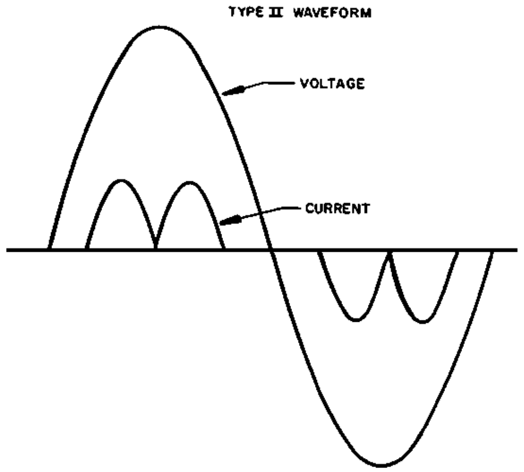


FIGURE 9B

AC LINE CURRENT WITH INVERTERS

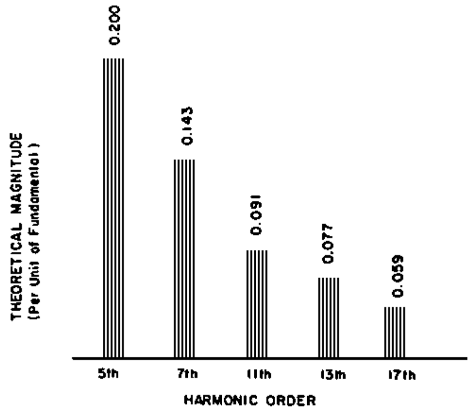


FIGURE 10

HARMONICS OF SIX-PULSE CONVERTER WITH WAVEFORM OF FIGURE 9A

For the waveform of Fig. 9B, the harmonics present can be predicted using the formula presented for the waveform of Fig. 9A. However, the magnitudes of the various harmonics is a function of the per phase inductance of the AC line connected to the adjustable frequency controller front end and the impedance of the adjustable frequency controller front end as "seen" by the AC lines. Typically, the calculation of the harmonic magnitudes of the waveform of Fig. 9B requires the use of a computer. However, the drive controller manufacturer should be able to supply the user a tabulation of the input current harmonics for a particular drive size and per phase inductance of the AC line at the feedpoint of the adjustable frequency controller. The user can usually determine the per phase inductance from the available short circuit capacity of the AC line at the controller feedpoint.

The presence of harmonics will cause the RMS current in the ac line feeding the adjustable frequency controller to increase.

The theoretical RMS current present in the circuit is the vector sum of all harmonic currents as represented by the following formula

$$I_{RMS} = I_f \sqrt{\sum_{h=1}^{\infty} I_{h}^{2}} \qquad (3)$$

Where: I_{RMS} is the RMS line current
h is the harmonic order
I_h is the per unit harmonic magnitude
I_f is the fundamental current

Since many factors influence the actual AC line currents of an adjustable frequency controller, there is generally no fixed relationship between the controller minimal output current and the controller nameplate input current. The required current carrying capacity of the branch circuit feeding the adjustable frequency controller must therefore be based on the nameplate input current of the adjustable frequency controller and not the nameplate horsepower of the controller or motor.

The distorted current due to harmonics combined with system feeder impedance results in distortion of the voltage on the branch circuit feeding the drive controller. A measure of the amount of distortion present is known as the Distortion Factor which can be calculated using the following formula:

$$DF = \sqrt{\sum_{h=2}^{\infty} \frac{V_{h}^{2} \times 100}{V_{f}^{2}}} \qquad (4)$$

Where: h = harmonic order
V_h = voltage of selected harmonic
V_f = voltage of fundamental

As was true with voltage transients, the presence of harmonics can cause problems. The problems can take several forms including:

1. Interfere with communications equipment
2. Overheating of transformers and motors
3. Equipment failures (severe cases)

As previously stated harmonics are present to some extent in all systems where solid state controllers are used, however, harmonics usually are not severe enough to cause problems. The main cause of harmonic related problems is the amplification of certain harmonics caused by circuit resonance at a harmonic frequency. This normally results when power factor correction capacitors are added to a system where harmonics are present. This condition and ways to minimize harmonic problems will be discussed further under the subject of power factor.

Power Factor:

The conventional explanation of power factor assumes a pure sine wave for current and voltage. This is usually associated with installations having contactors and no power semiconductors. In these cases, power factor is defined as the cosine of the displacement angle between voltage and current. The current displacement is usually the result of inductive or capacitive system reactances.

This concept of power factor is shown in Figures 11 and 12.

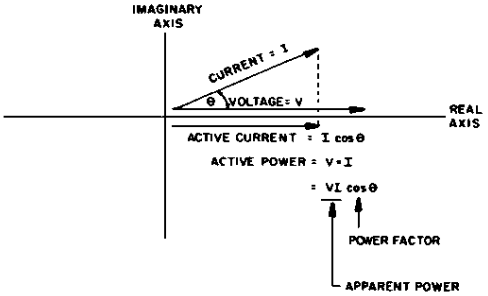


FIGURE 11
CONVENTIONAL VECTOR DIAGRAM FOR POWER FACTOR

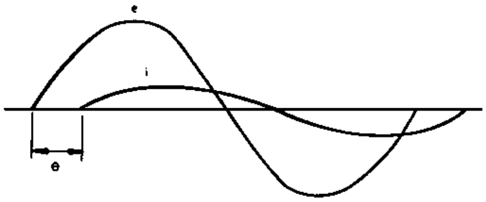


FIGURE 12
TYPICAL WAVE FORM SHOWING LAGGING CURRENT

The angle θ represents a phase shift or displacement between voltage and current when pure sinusoidal (undistorted) wave forms exist. Typical wave forms are illustrated in Figure 12.

When discussing power factor for systems utilizing power semiconductor devices such as adjustable frequency controllers, the concept of a displacement angle between a non-sinusoidal voltage and current becomes complex. In addition to the displacement between the fundamental of voltage and current caused by the circuit reactances, an SCR converter stage is capable of introducing additional displacement between the fundamental of voltage and current by controlling the firing point of the SCR's with respect to the fundamental voltage. This is done typically to control the converter output voltage. This process is sometimes known as phase control of the SCR's.

A third element which must be considered is the effects of the harmonics contained in the current and voltage waveforms. The concept of a displacement angle totally breaks down when attempting to deal with harmonics. Therefore, it becomes necessary to re-evaluate our thinking about power factor. To this end, an inspection of Fig. 11 is in order. Note that the product of the RMS voltage and RMS current is the apparent power in the system; apparent power being measured in volt-amperes (VA). The active power, or working power, is measured in units of watts (W). Therefore, the power factor could have been computed from the ratio of the active power (as measured by a wattmeter) to the apparent power (as measured with an RMS voltmeter and ammeter). To prevent confusion, the ratio of active to apparent power will be called total power factor, or utilization factor.

The definition of total power factor works equally well for systems containing non-sinusoidal voltages and currents. All the data required to determine utilization factor can be computed or measured. There are no ambiguous quantities as was the case with the concept of a displacement angle between fundamental voltage and current.

Total power factor (utilization factor) can be viewed as containing two terms. One term, known as the displacement power factor is roughly equivalent to the displacement angle power factor seen on systems containing only sinusoidal voltages and currents. In addition, the displacement power factor considers the effects of the artificial displacement created by SCR phase control converters. The second term, known as the distortion power factor, considers the effects of the harmonics. This term is essentially a quality factor for the non-sinusoidal waveforms. The closer the distortion power factor is to unity, the more the non-sinusoidal waveforms resemble sine waves. For a system with sinusoidal voltages and currents, the distortion power factor is unity.

The relationship between total power factor (utilization factor), displacement power factor, and distortion power factor is as follows:

Total power factor = displacement power factor X distortion power factor (utilization factor)

Distortion power factor is typically not measured by utility metering equipment. Utilities typically meter only the displacement component so there is no direct penalty for poor distortion power factor. The penalty shows up in the form of increased demand (KVA) on the distribution system which reduces the system efficiency.

Total power factor as described above would be the vector sum of the displacement component and the distortion component. This is represented as a three-dimensional vector diagram in Figure 13.

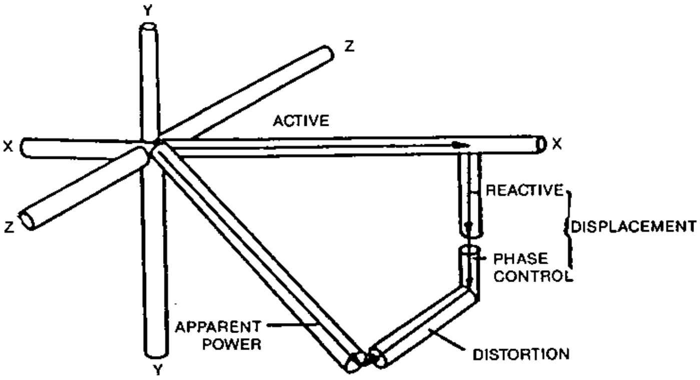


FIGURE 13
VECTOR DIAGRAM OF TOTAL POWER FACTOR WITH SOLID STATE CONTROL

The negative effects of power factor include the following:

- Reduced distribution system capacity
- Reduced distribution system efficiency
- Possible penalty charge by the utility

The negative effects of adjustable frequency controllers on power factor can be reduced by proper selection of adjustable frequency controllers and careful use of power factor correction capacitors when required. When selecting a controller, consideration should be given to those having diode or diode with chopper front ends since both of these types exhibit a displacemet power factor of about .95 lagging over the full speed range. If a controller using an SCR front end is selected, it is possible to correct the displacement power factor for only one speed point.

The addition of power factor correction capacitors can result in a severe harmonic problem by setting up a tuned circuit with system inductances. If the parallel resonant circuit shown in figure 14 happens to tune to a harmonic frequency, the harmonic current will be amplified, possibly to damaging levels. It is therefore possible by correcting one problem to create or worsen another problem.

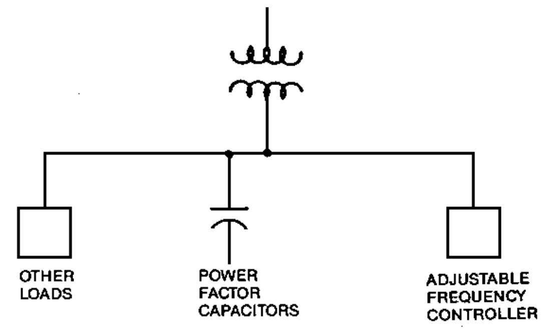


FIGURE 14A
SYSTEM ONE—LINE FOR PARALLEL RESONANT

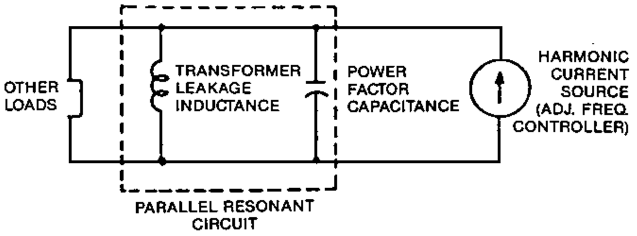


FIGURE 14B
PARALLEL RESONANT CIRCUIT

If it is necessary to add power factor capacitors to a system with a significant portion of the connected load made up of solid-state motor speed controllers or rectifier power supplies, an approach shown in Figure 15 can be used.

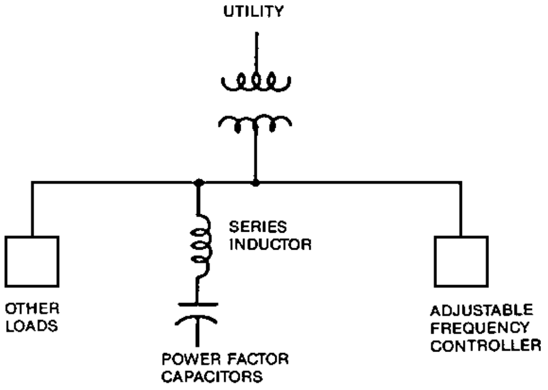


FIGURE 15A
SYSTEM ONE-LINE WITH ADDITION OF TUNING INDUCTOR

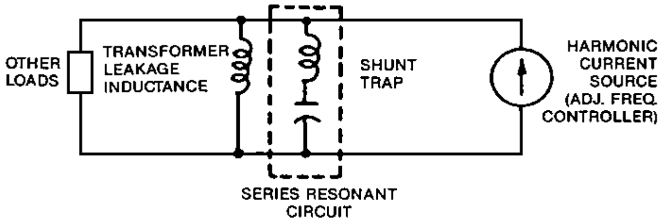


FIGURE 15B
CIRCUIT WITH ADDITION OF TUNING INDUCTOR

This technique involves the addition of series inductor to tune the circuit away from a harmonic frequency and trap harmonic currents. In cases where a severe harmonic problem exists, it may be necessary to remove the harmonic currents using filters.

While this would look similar to the circuit shown in Figure 15, the tuning inductor is selected to tune with the capacitors to a particular harmonic frequency thereby shunting that frequency and dissipating its energy as heat in the inductor capacitor network. Multiple traps can be employed to remove several problem harmonics. It is necessary to start with the lowest order harmonic present and work upward to prevent the trap for a higher order harmonic from causing a resonance problem at a lower frequency.

In order to minimize adverse effects of solid state controllers on a power system, IEEE 519-1981 sets recommended limits for voltage distortion and line notching. Recommended maximums for line notching vary from 16,400 volt-microseconds for sensitive systems to 36,500 volt-microseconds for less sensitive systems. Recommended maximums for distortion factor vary from 3% to 10% for the same conditions.

For adjustable frequency controllers using diode or diode with chopper front ends line notching is negligible, normally in the range of 500-1000 volt-microseconds. The distortion factor depends upon many variables such as the source KVA and system impedances in addition to characteristics of the controller such as full load current, capacitance of dc bus filter capacitors, etc. To predict the actual value of input RMS current and distortion factor for a particular installation, a controller manufacturer would have to perform a thorough analysis of the installation. Another approach would be to produce a set of curves to cover a wide range of conditions. An example of this is shown in Figure 16. These curves plotted from computer generated data show input current and voltage distortion versus line inductance for a 5 horsepower 460 volt adjustable frequency controller with a rated output current of 7.6 amperes.

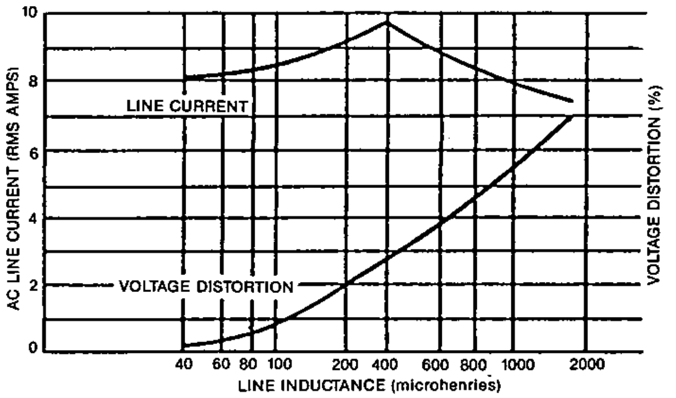


FIGURE 16
LINE CURRENT & VOLTAGE DISTORTION vs. LINE INDUCTANCE

To summarize, the effects that adjustable frequency controllers have on the ac line are primarily dependent on the type of converter stage used to change line ac voltage to dc voltage. The ac line will be subjected to voltage transients or line notching, distorted current and voltage and a reduction in total power factor. If controllers using SCRs to change line ac to variable voltage dc are used and power factor correction is required, power factor correction capacitors must be applied very carefully to avoid a resonant condition.

The use of adjustable frequency controllers can be expected to increase dramatically in coming years. This means increased potential for adverse effects on power distribution systems. The best way to avoid problems is to gain an understanding of potential problems and ways to minimize these problems.

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