FERRORESONANT TRANSFORMER

1.0 PHYSICAL CHARACTERISTICS OF THE FERRORESONANT TRANSFORMER

Figure 1.0 presents the geometry of a one-piece ferroresonant regulator. There is an input winding N1, which is connected to the source of power, a magnetic shunt, an output winding NL which can be connected to a rectifier-filter arrangement to produce a DC output or to supply an AC voltage. A third winding NC which is connected to the resonating capacitor.

1.1 PRINCIPLE OF REGULATING ACTION

When the regulator goes into a ferroresonant condition of operation, (the mechanism of ferroresonance is explained in Section 1.2) the portion of the magnetic circuit shown cross-hatched in Figure 1.0 is driven very far into saturation. The hysteresis characteristic of the magnetic material under this condition of operation is shown in Figure 1.1.

When the regulator is operating at a no load and high input line, the B-H curve operates between points 1 and 1' giving a change in the flux density through the output winding of B1. At the other extreme condition of operation, full load, low input line, the B-H curve operates between points 2 and 2' giving a change in the flux density of B2' Since B1, is very nearly equal to B2, the output voltage remains very nearly constant throughout the entire range of operation. This is the principle of regulating action.

1.2 MECHANISM OF FERRORESONANCE

Ferroresonance is a special case of the "jump phenomenon" which occurs in periodic, nonlinear, magnetic systems when the system has a transition from a state of unstable or semistable equilibrium to a state of stable equilibrium. The system is characterized by a pronounced, discontinuous change in the steady state amplitude of the oscillations in one or more of its system variables.

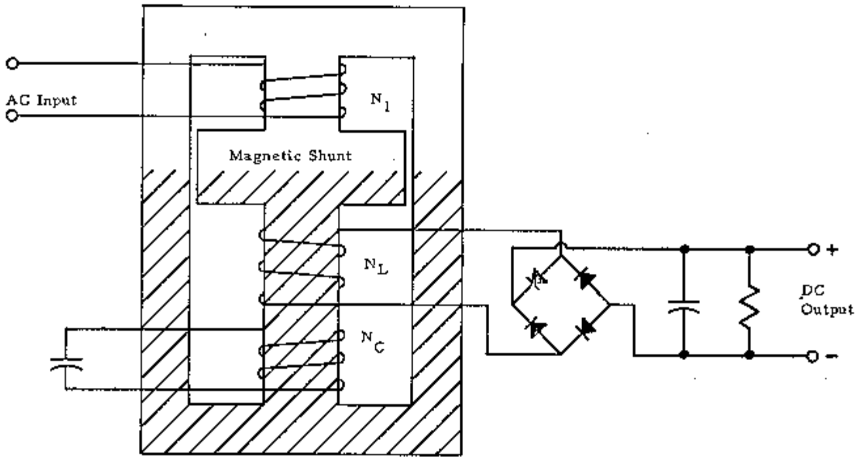


Figure 1.0

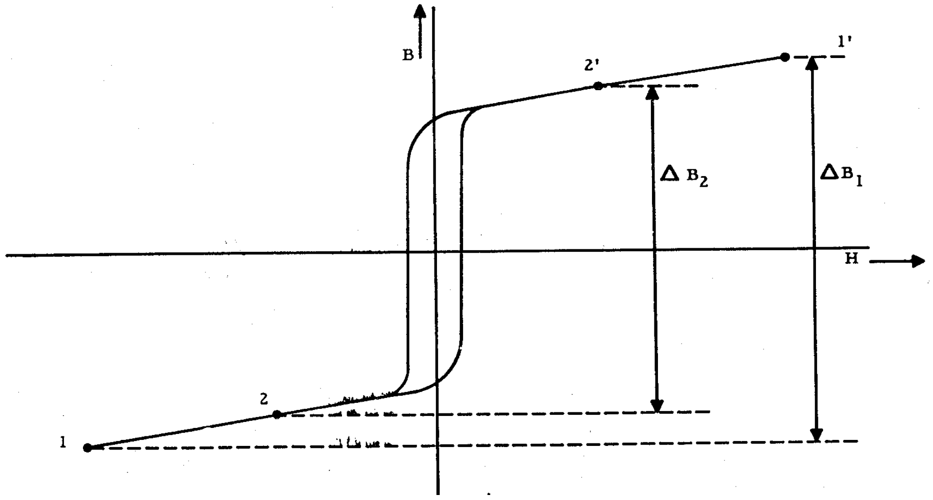


Figure 1.1

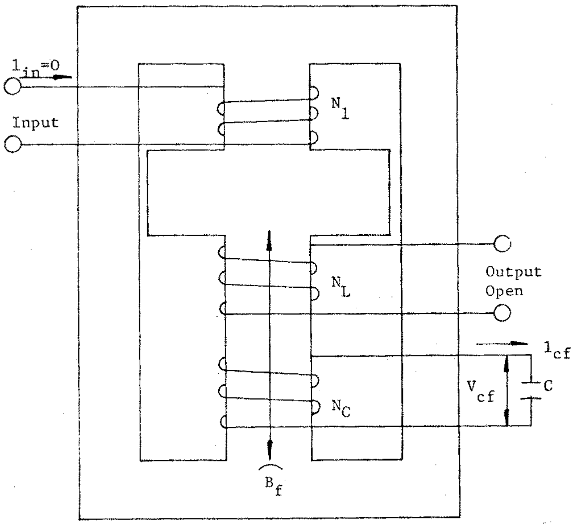
The mechanism of ferroresonance can be most easily be explained if one considers the operation of the one-piece regulator under the special condition of no load on the output winding, and a theoretically idealized, lossless condition of operation at no load. Figure 1.2 shows the conditions, which would exist under this kind of operation.

Since the load circuit is open, there are no load ampere-turns acting in the magnetic circuit. Furthermore, if the input voltage is small compared to rated voltage and lossless operation is assumed, we can neglect the input ampere turns as being small compared to the capacitor winding ampere turns. Essentially, we are saying that we will consider a condition of operation where the only ampere-turns of importance acting in the magnetic circuit are those of the capacitor winding. Moreover, because the voltages and currents of the regulator are nonsinusiodal periodic functions, we make these definitions:

Icf is the RMS value of the fundamental component of capacitor current.

Vcf is the RMS value of the fundamental component of capacitor voltage.

Bf is the maximum value of the fundamental component of magnetic flux density through the capacitor winding turns Nc



Idealized No-Load Operation of One-Piece Ferroresonant Regulator

Figure 1.2

Now, Icf = 2PI fC Vcf and Vcf = Kf Nc Bf

PI=3.14159

Where K is a constant.

so that NC IcF = 2PI K NC^2 F^2 C BF

Figure 1.3 gives a plot of the magnetization curve of the magnetic material employed in the construction of the regulator using Bf and NcI cf as axes. The straight line of equation (3) is also plotted in Figure 1.3.

In the region AB, the ampere turns required to establish a flux density Bfl are A2, which are greater than the ampere turns available Al. This is a stable region of operation. However, in the region BC, the ampere turns required to establish a flux density Bf2 are A3, which are less than the ampere turns available A4. Region BC is, therefore, an unstable region of operation. As the input voltage is slowly increased from zero, the fundamental output voltage which is proportional to Bf increases slowly until point B is reached at which point the steady-state output voltage quickly jumps to the much higher value associated with point C -- a point of stable equilibrium. The mechanism of ferroresonance causes the portions of the magnetic circuit shown crosshatched in Figure, 1.0 to be driven very far into saturation giving the regulator its constant voltage characteristic.

FUNCTION OF THE MAGNETIC SHUNT

The function of the magnetic shunt is twofold; first to magnetically decouple the input from the output so that the ferroresonant action can proceed independently of the input. Secondly, after ferroresonance has occurred, it provides a path for changes in the input magnetic flux caused by changes in the input voltage to be shunted around the magnetic path associated with the output winding. This means that the output voltage will be very insensitive to either large static or dynamic changes in-the input voltage. An attenuation of 10 to 1 is normally achieved. This is the most significant advantage of the regulator.

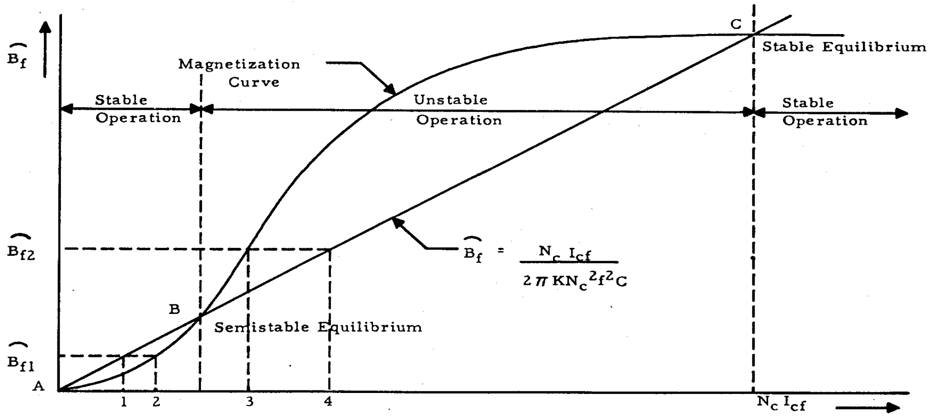


Figure 1.3

1.4 OUTPUT CHARACTERISTIC

The output characteristic of the ferroresonant regulator power supply is illustrated in Figure 1.4. In the range from no load to full load (0 - 100%) the line regulation, both static and dynamic, will be approximately ± 1% for a 10% change in the input line voltage.

The load regulation, on the other hand, will be much greater because of the inherent internal regulation of the transformer as it is loaded, which was discussed as the difference between B1 and B2 in Figure 1.1. Moreover, additional load regulation is produced by voltage drops associated with the resistance and leakage inductance of the transformer windings.

The static load regulation, as the load is changed from 10% to 100% of full load, will be approximately 5% for output voltages greater than 50 volts. For lower output voltages, the static load regulation increases being approximately 10% for an output of 5 volts. The regulation can be tightened with the addition of a compensation winding. This winding is placed on the primary side and is wound over the primary winding. This winding is placed in series with the output winding to compensation for changes in the load. With the addition of the compensation winding the line and load regulation can be tightened to +/- 2 %.

As load current flows through the load winding, ampere-turns are produced which oppose the magnetizing ampere-turns of the capacitor winding. Finally, as the load current is increased, the demagnetizing effect of the load ampere turns overcomes the magnetizing effect of the capacitor winding ampere turns dropping the regulator out of ferroresonance. The transformer then behaves essentially as a high reactance transformer and inherently limits its short circuit current (see Figure 1.4) between 150 and 200 % of rated current. The regulator, therefore, provides inherent short circuit protection for itself and associated circuitry.

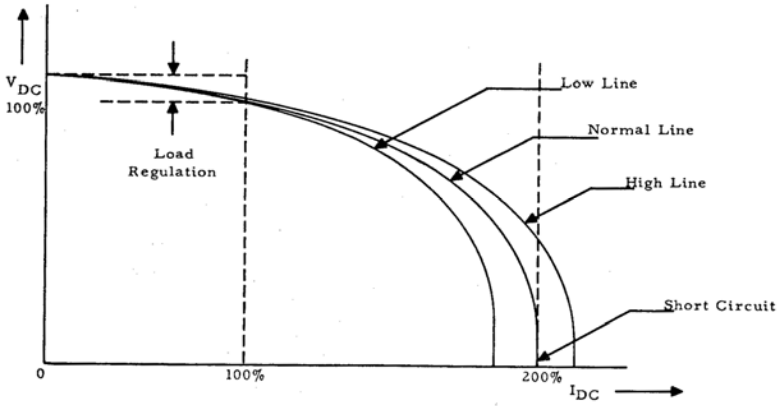


Figure 1.4

1.5 OUTPUT WAVEFORM

The voltage output waveform of the ferroresonant transformer appears as shown in Figure 1.5. This trapezoidal waveform has these two important advantages for rectification and filtering to DC.

1. There are no voltage spikes on the output waveform, which could damage rectifiers or require more expensive, higher voltage-rating rectifiers to be used.

2. Since the trapezoidal waveform approaches the ideal square waveform, the amount of filter capacity required to obtain the same peak-to-peak ripple is approximately 20% less than the filter capacity required for a rectified sine-wave of voltage.

The disadvantage of this voltage wave shape is that it has approximately 30 % harmonic distortion. This wave shape would be unsuitable for application requiring a sine output.

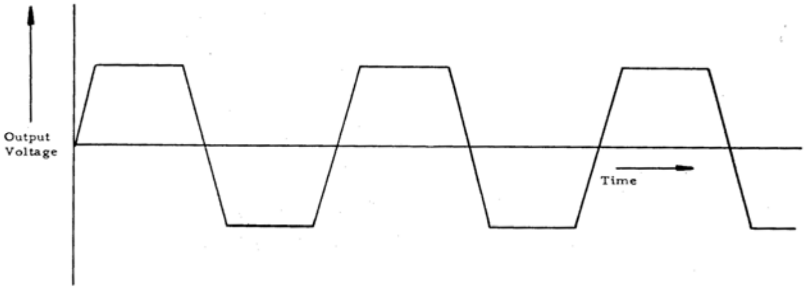


Figure 1.5

1.5.5 Output wave shape filtering.

Figure 1.5.5 shows a modified core geometry that retains all of the ferroresonant transformer characteristics. Also it produces an output voltage sine wave with less than 5 % total harmonic distortion. The geometry of fig. 1.5.5 differs from that shown in fig. 1.0 in that it has an additional magnetic circuit. The resonant winding and the secondary winding along with the capacitor cause the center portion of the core to operate in saturation. The addition of the harmonic neutralizing winding with the proper leakage reactance cancels the voltage harmonics resulting in a sine wave output voltage.

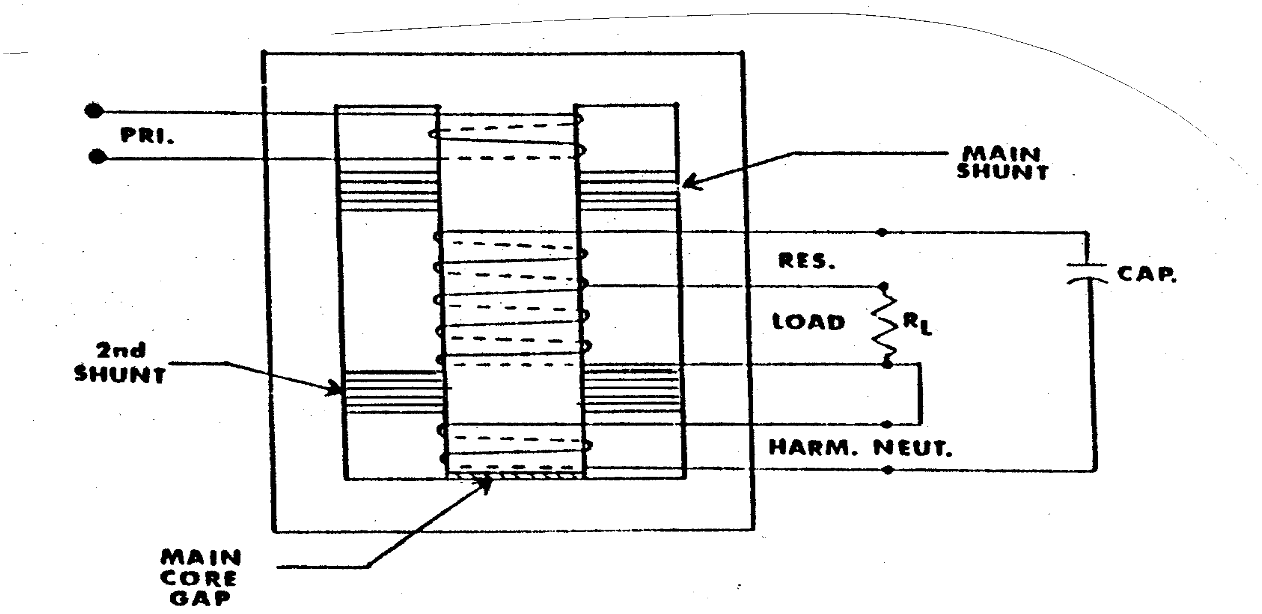


Figure 1.5.5

1.6 INPUT CHARACTERISTIC

Figure 1.1 presents the input characteristics of the ferroresonant transformer. As the input voltage is increased from zero towards nominal line voltage (NL) the regulator jumps into ferroresonance at point 1 for no load and point 2 for full load. The regulator is designed so that the full load jump-in point is approximately 15 to 20 % below the low-line input voltage (LL).

Furthermore, the regulator is also designed so that the minimum input current characteristic occurs approximately at the high line (HL). This design consideration gives the best input power factor characteristic over the entire range of line voltage variation. To understand why this is true, consider the equation for determining the input power factor -

$$\text{p.f.} = \underline{(\text{watts Input average})/}\ (\text{Input RMS volts}) \times (\text{Input RMS amperes})$$

As we change the input voltage from low-line to high-line at a fixed load, the input power remains essentially constant, hence in order to maintain a nearly constant power factor it is necessary that the input current decrease as the input voltage increases. This is exactly the characteristic illustrated in Figure 1.6.

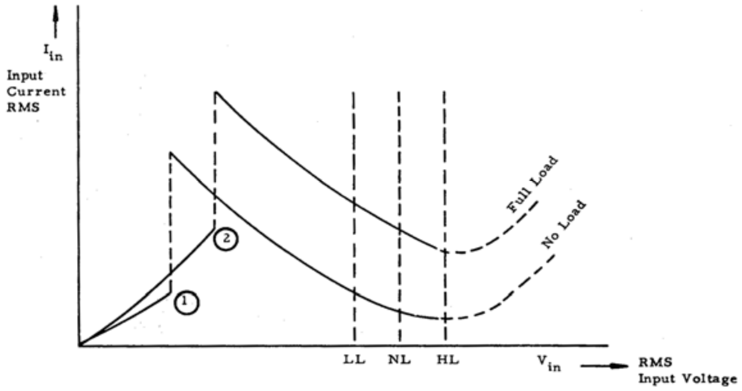


Figure 1.6

Full load input power factors run in the range of 85 - 98%. Moreover, full load efficiencies will reach 85% for DC power supplies supplying 500 watts of output power. Efficiencies of 92 % are attainable with AC supplies.

1.7 TRANSFER CHARACTERISTIC

The transfer characteristics are shown in Figure 1.7. Note again the excellent regulation obtained with varying input line voltage and also the relatively poorer load regulation.

1.8 FREQUENCY SENSITIVITY

Referring to Figure 1.3, we see that the slope of the straight line varies inversely with the square of the input frequency. As the frequency increases, the slope of the straight line decreases and point C moves up to a higher value of flux density. The output voltage of the regulator is, therefore, sensitive to frequency variations, the relation being a 1.4% change in output voltage for a 1% change in input frequency.

1.9 TEMPERATURE DRIFT

When the temperature of the magnetic core material is increased, the saturation flux density usually decreases. Figure 1.8 shows the general relation between temperature and saturation flux density for silicon steel.

Since the principle of regulator action depends on the magnetic material being driven into saturation, any change in the saturation flux density will produce a change in the output voltage. The normal temperature drift that one can expect for warmup and an ambient temperature change from 0 to 60 degrees is approximately 1 %.

2.0 EXTERNAL MAGNETIC FIELDS

Because certain portions of the magnetic structure of ferroresonant regulators operate at high saturation flux densities, the leakage magnetic field surrounding these structures is high. If these stray magnetic fields are an important consideration, this can be reduced by the addition of magnetic shielding

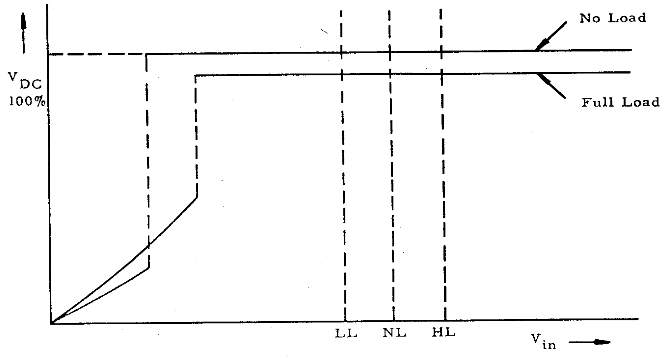


Figure 1.7

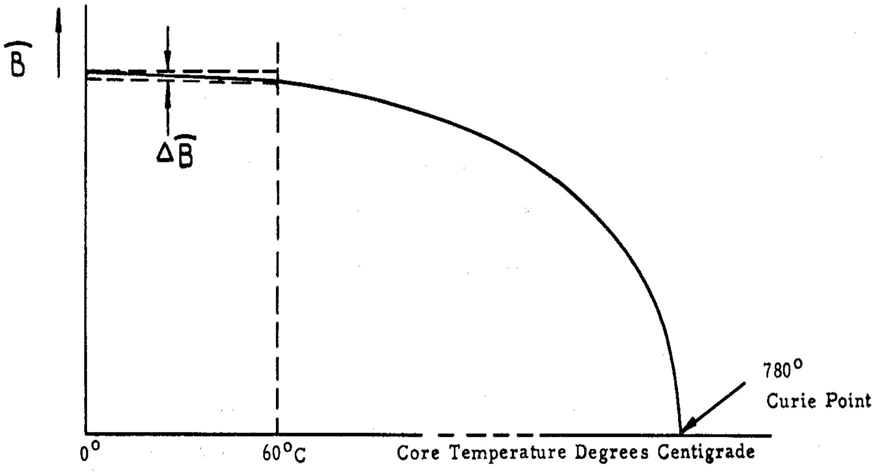


Figure 1.8

2.0 ADVANTAGES AND DISADVANTAGES

The ferroresonant transformer is used for applications allowing moderately large percentages of overall regulation bandwidth (Ex. ± 5% to ± 10%). It is the simplest, lowest cost, and most reliable transformer available today for producing large amounts of regulated DC or AC power.

When the ferroresonant transformer is designed using compensation windings, as explained in par. 1.4, the resultant power supply system is capable of achieving extremely small bandwidths of voltage regulation (<± 2%) for large amounts of power at low cost and high efficiency.

The advantages of the ferroresonant power supply are:

1. It is a regulating transformer and provides voltage isolation and sets the output voltage level.
2. Reliable.
3. Very good voltage regulation with static and dynamic input line voltage changes.
4. Provides inherent short circuit protection.
5. Output waveform protects rectifiers and requires smaller filter in DC applications.
6. Good efficiency and input power factor.
7. Isolated multiple outputs.

The disadvantages are:

1. Frequency sensitive.
2. Poorer regulation for large static or dynamic load power changes.
3. External magnetic field may produce undesirable pickup if the transformer is not shielded.