# CHAPTER 3

## The Saturable Reactor

The simplest saturable reactor consists of a single ferromagnetic core (either rectangular or circular) having two windings, namely an a-c coil or load winding NL and a d-c or control winding $N_C$. This reactor is shown in Fig 6.

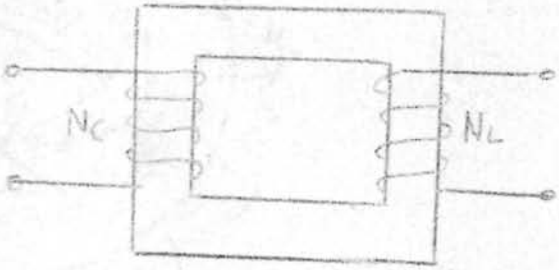

Fig 6. Simplest saturable reactor

For circuit operation, the control winding is connected to a source of d-c control voltage and the load winding is connected in series with the load a supply of a-c voltage, as shown in Fig 7.

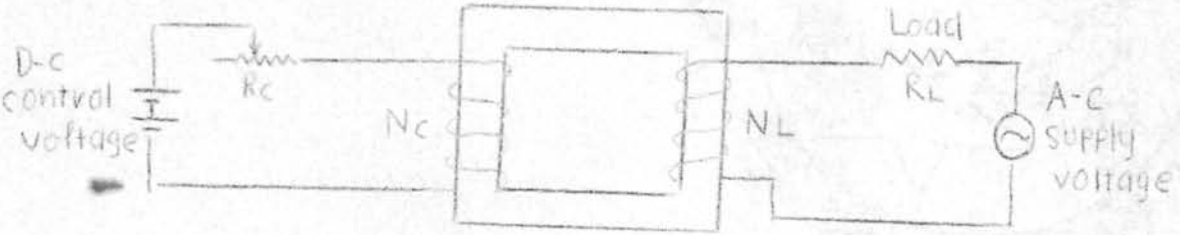

Fig 7. Simplest saturable reactor connected in circuit.

When the control current is varied, the impedance of the load winding is changed, thereby determining the voltage output appearing across the load. One of the problems existing in the fundamental reactor of Fig 7 is that the mutual induction between the d-c and a-c windings causes interaction between the control and load circuits. In order to reduce this effect, two separate core elements with series control and series load windings, are used, as shown in Fig 8.

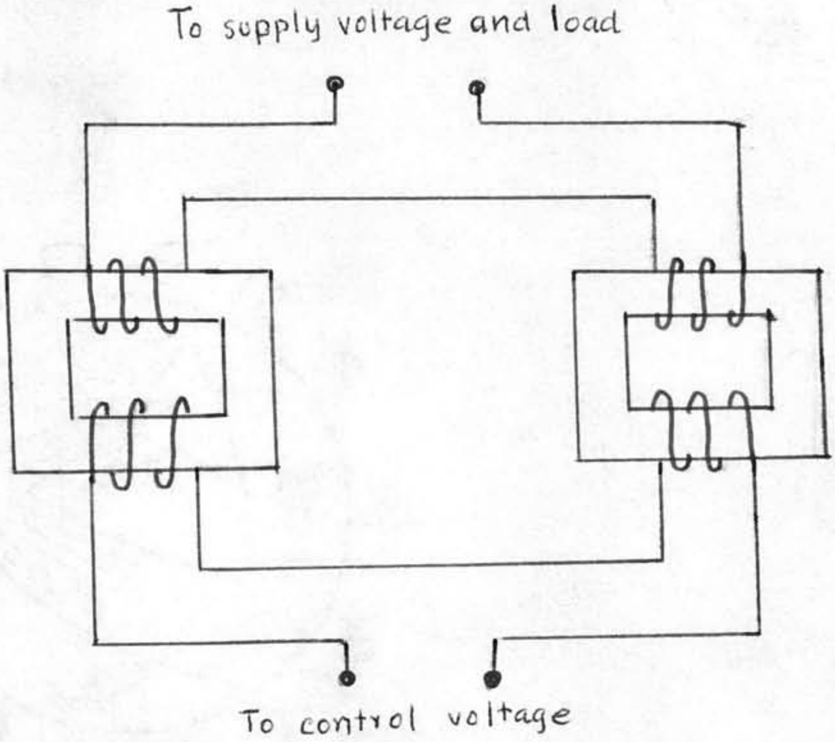

Fig 8. Saturable reactor having two cores to reduce mutual induction.

By this circuit arrangement, the induced voltages cancel each other, thereby reducing the unwanted effects.

The most common basic saturable reactor consists of a three-legged closed laminated core, with coil wound on each leg. The control winding is wound on the middle leg and the two load windings are wound on the outer legs.

Core Materials for Saturable Reactors.

For optimum performance, the core material should have the following magnetic properties:

1. Hysteresis and eddy-current losses a minimum (high resistivity, low coercive force, and ability to be made in thin laminations or tapes).

2. High saturation flux density, to obtain large power-power-handling capacity of a given weight of core material.

3. The general shape of the magnetization curve as close as possible to the rectangular histeresis loop, as shown in Fig 9.

4. Stability of magnetic characteristics under changing temperature and mechanical strain and shock condition.

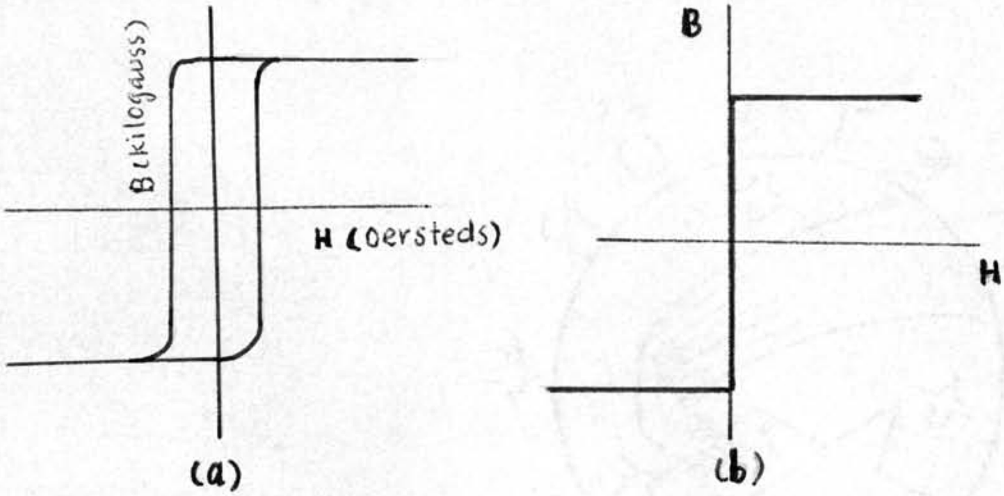

Fig 9. Rectangular hysteresis loops a) actual magnetization curve, b) idealized magnetization curve.

## Current and Voltage Relationships, Forced Magnetization.

The relationship between control and load currents can be derived with reference to the flux produced by the winding. Assume that a sinusoidal voltage is applied to the load circuit. The current flowing through the coil setsup a magnetic field proportional to the magnitude of the current and the state of magnetization of the core. If the core is below magnetic saturation, the changing flux causes a counter voltage to be induced in to the coil, of amplitude and polarity such as to oppose the voltage that produced it. This results since the applied sinusoidal voltage produces a current lagging by 90 degrees (in a purely inductive circuit), which in turn produces a flux wave lagging the applied voltage by the same 90 degrees. The counter emf generated lags an additional 90 degrees behind the flux, so that a total of 180 degrees exists between the applied and counter voltages.

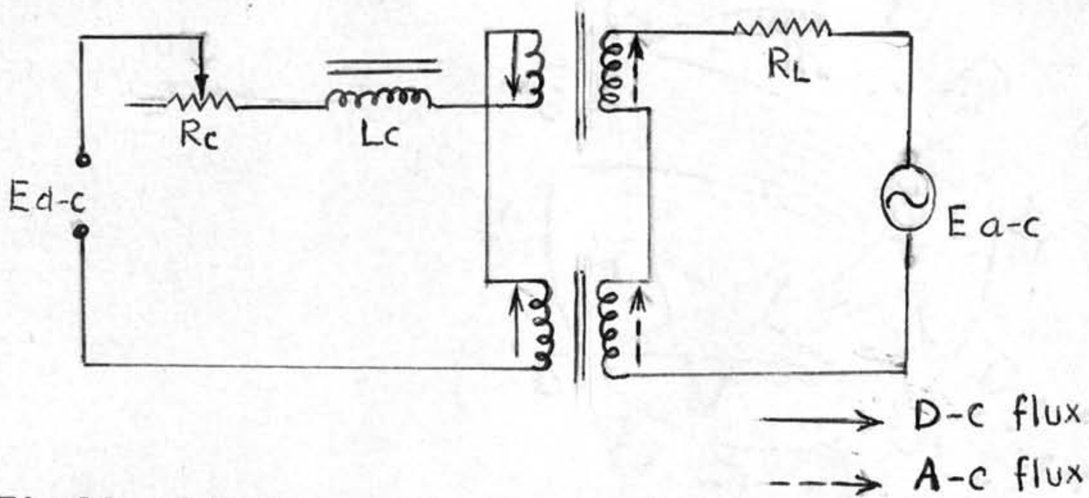

Fig 10. Forced magnetization condition.

The shape of the waveforms encountered in a saturable reactor is determined largly by the magnitude of the harmonic currents which flow in the control circuit. The presence or absence of these currents is dependent upon the circuit arrangement. For example, consider the circuit of Fig 10, wich has series-connected a-c windings and in which a choke is used to limit extraneous currents induced into the control circuit. The presence of the choke causes the control circuit to present a high impedance to the relatively h high-magnitude even harmonic currents, thus tending to suppress them, this sets up a condition referred to as "forced or constrained magnetization", i.e., even-harmonic currents are not permitted to flow freely. The term forced magnetization derives from the fact that the choke prevents the d-c control current from varying, regardless of what happens in the a-c windings, thereby forcing the magnetization to remain at the level determined by the d-c current alone. This condition may also be designated as one of "suppressed even-harmonic currents."

### Natural Magnetization.

In a saturable-reactor circuit with series-connected a-c windings and a low impedance control circuit (no series choke), even harmonic currents are not damped out, but rather flow freely in the control network. This represents the condition of "natural magnetization", and is the condition under which most reactors operate.

## The saturable reactor circuit.

One of the simplest arrangements has a single-saturable-core reactor with two windings $N_C$ and $N_L$. The load winding $N_L$ is connected to a source of alternating current, through a load represented by the load resistor $R_L$ (e.g., a bank of lamps) carrying the load current $I_L$. The control winding $N_C$ is supplied

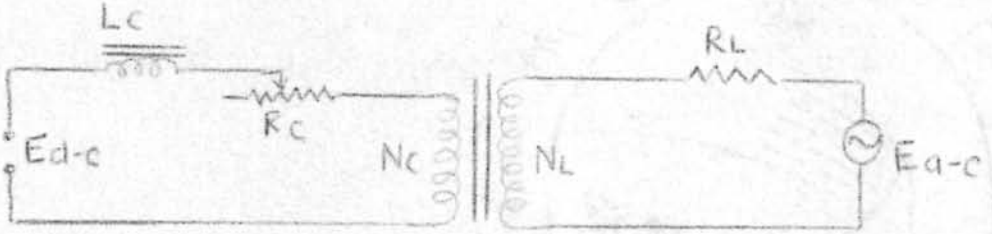

Fig 11. The basic saturable reactor circuit.

with direct current $I_C$ from the d-c source through the variable resistor $R_C$ and an iron-core choke coil Lc. This coil presents a very high impedance to alternating current sothat the voltage induced from the load winding $N_L$ into the control winding $N_C$ is unable to produce excessively large circulating currents in the control circuit loop.

The operation of this circuit is based upon the fact that the actual impedance of the saturable reactor is determined by the direct current flowing in the control winding. When the current $I_C$ is at its minimum value, as determined by the maximum resistance of $R_C$, the inductive inductance of

$N_L$ is maximum and the load current $I_L$ is minimum. The a-c voltage developed across the load is at its lowest value. As the resistance Rc is decreased so that the current Ic in the control circuit increases, the impedance of the load winding is reduced, accordingly, and the load current $I_L$ increases. The load voltage thus increases as the d-c magnetization of the reactor increases. At core saturation, the impedance $N_L$ reaches its lowest value and the load current and voltage will have its highest value. The value of inductance of a coil is determined by the equation.

$$L = \frac{N\phi}{I \times 10^8} \text{ henry.}$$

Where L = inductance in henries.

N = number of conductors linked by magnetic flux.

$\phi$ = total number of flux linkages in maxwells.

I = current producing the magnetic flux, in amperes.

From this equation, it can be seen that the inductance is proportional to N $\phi$, If $\phi$ or N is increased, the inductance of the coil increases. In the case of the coil characteristics previously specified, the inductance would be increased if:,

1) A greater number of turns of wire were added to the coil.

2) The spacing between adjacent turns were decreased.

3) A core of high permeability were used.

For a solinoid, the empirical formula for its inductance is

$$L = \frac{1.26\, N^2 \mu\, A}{1 \times 108} \quad \text{henry.}$$

where $L$ = inductance in henries.

$N$ = number of turns in solinoid.

$\mu$ = permeability of the core.

$A$ = area of the core in square centimeters.

$l$ = length of the corein centimeters.

In a magnetic amplifier circuit the term "inductive reactance" is introduced. The inductive reactance limits the flow of alternating current in the load circuit. (No inductive reactance is established by the coil in the presence of a pure direct current, since no relative motion exists between the magnetic flux and the coil).

The inductive reactance of a circuit is given as follows:-

$$Xl = 2\pi f \cdot L$$

where $Xl$ = inductive reactance in ohms.

$f$ = frequency of the supply voltage in cycles per second.

$L$ = inductance of the circuit in henmies.

The introduction of inductive reactance into the circuit offers an opposition to the current flowing in the circuit, and results in the current being lower than it would be if no inductance were present. In a pure inductive circuit, the current in the circuit may be determine by the a-c Ohm's law in the following manner

$$I = \frac{E}{Xl}$$

Where $I$ = current in amperes

$E$ = emf of the source voltage in volts

$Xl$ = inductive reactance.

$X_1$ = indutive reactance.

In a circuit containing both resistance and inductance, the opposition to the current is a vector quantity called the impedance and signified by Z. In the R-L circuit, the impedance is

$$Z = R^2 + X_1^2$$

where Z = total impedance in ohms.

R = resistance of the circuit in ohms.

$X_1$= inductive reactance of the circuit in ohms.

The circuit current is

$$I = \frac{E}{Z}$$