# Ferro resonance

The term *Ferro resonance* refers to a special kind of resonance that involves capacitance and iron-core inductance. The most common condition in which it causes disturbances is when the magnetizing impedance of a transformer is placed in series with a system capacitor. This happens when there is an open-phase conductor. Under controlled conditions, ferroresonance can be exploited for useful purpose such as in a constant-voltage transformer.

Ferroresonance is different than resonance in linear system elements. In linear systems, resonance results in high sinusoidal voltages and currents of the resonant frequency. Linear system resonance is the phenomenon behind the magnification of harmonics in power systems. Ferroresonance can also result in high voltages and currents, but the resulting waveforms are usually irregular and chaotic in shape.

The concept of ferroresonance can be explained in terms of linear-system resonance as follows.Consider a simple series *RLC* circuit as shown in Fig. 3.6. Neglecting the resistance *R* for the moment, the current flowing in the circuit can be expressed as follows:

$$I = \frac{E}{j(X_L - X_C)}$$

Where $E$ = driving voltage

$X_L$ = reactance of $L$

$X_C$ = *reactance of C*

When $XL = |XC|$, a series-resonant circuit is formed, and the equation yields an infinitely large current that in reality                                                 would be limited by $R$.
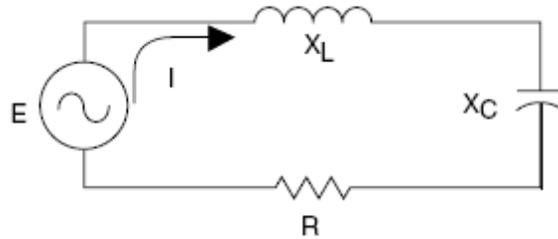


**Figure 3.6 Simple series *RLC* circuit**

An alternate solution to the series *RLC* circuit can be obtained by writing two equations defining the voltage across the inductor, i.e.

$$v \square jX_L I \, ,$$

$$v \square E \square j X_C I$$

Where $v$ is a voltage variable.

Figure 3.7 shows the graphical solution of these two equations for two different reactances, $X_L$ and $X_{L'}$. $X_{L'}$ represents the series-resonant condition. The intersection point between the capacitive and inductive lines gives the voltage across inductor $E_L$. The voltage
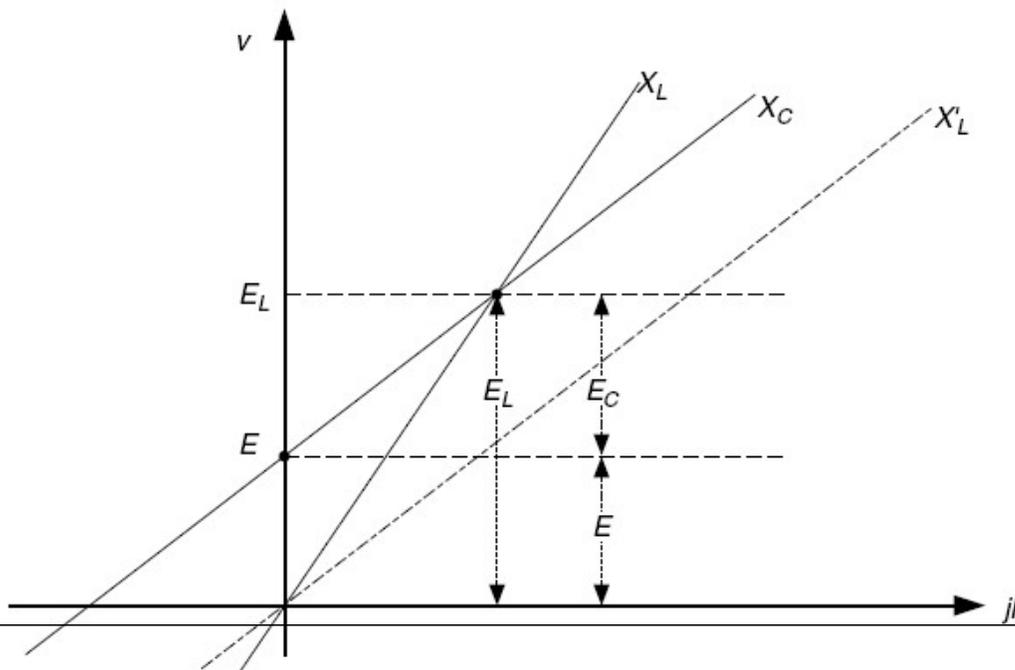
across capacitor $E_C$ is determined as shown in

Fig. 3.10. At resonance, the two lines will intersect at infinitely large voltage and current since the $|X_C|$ line is parallel to the $X_L'$ line.

**Figure 3.7** Graphical solution to the linear $LC$ circuit

Now, let us assume that the inductive element in the circuit has a nonlinear reactance characteristic like that found in transformer magnetizing reactance. Figure 3.8 illustrates the graphical solution of the equations following the methodology just presented for linear circuits.
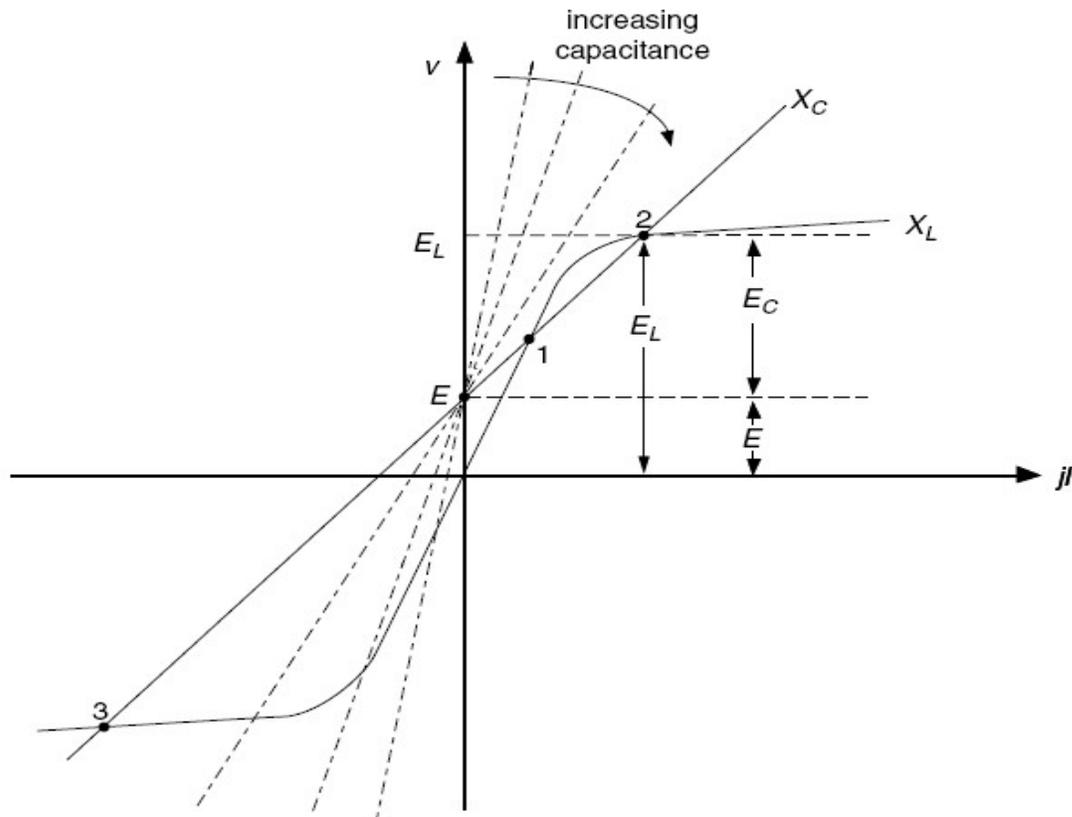
**Figure 3.8** Graphical solution to the nonlinear *LC* circuit

It is obvious that there may be as many as three intersections between the capacitive reactance line and the inductive reactance curve. Intersection 2 is an unstable solution, and this operating point gives rise to some of the chaotic behavior of ferroresonance. Intersections 1 and 3 are stable and will exist in the steady state. Intersection 3 results in high voltages and high currents.

Figures 3.9 and 3.10 show examples of ferroresonant voltages that can result from this simple series circuit. The same inductive characteristic was assumed for each case. The capacitance was varied to achieve a different operating point after an initial transient that pushes the system into resonance. The unstable case yields voltages in excess of 4.0 pu, while the stable case settles in at voltages slightly over 2.0 pu. Either condition can impose excessive duty on power system elements and load equipment.

For a small capacitance, the $|X_C|$ line is very steep, resulting in an intersection point on the third quadrant only. This can yield a range of voltages from less than 1.0 pu to voltages like those shown in Fig. 3.13.
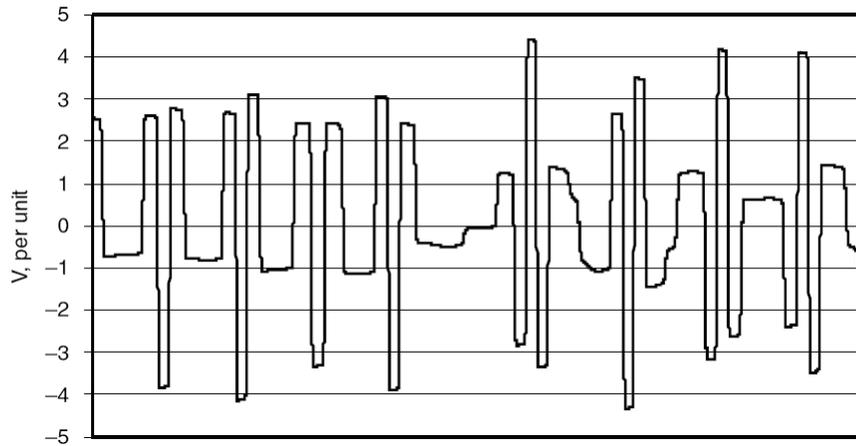


**Figure 3.9** Example of unstable, chaotic ferroresonance voltages

When $C$ is very large, the capacitive reactance line will intersect only at points 1 and 3. One operating state is of low voltage and lagging current (intersection 1), and the other is of high voltage and leading current (intersection 3). The operating points during ferroresonance can oscillate between intersection points 1 and 3 depending on the applied voltage. Often, the resistance in the circuit prevents operation at point 3 and no high voltages will occur.
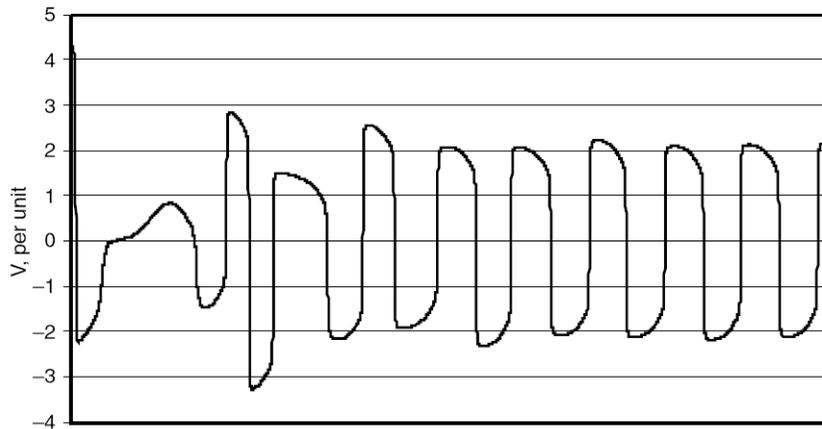
**Figure 3.10** Example of ferroresonance voltages settling into a stable operating point (intersection 3) after an initial transient.

The most common events leading to ferroresonance are

- Manual switching of an unloaded, cable-fed, three-phase transformer where only one phase is closed (Fig. 3.11 *a*). Ferroresonance may be noted when the first phase is closed upon energization or before the last phase is opened on deenergization.

- Manual switching of an unloaded, cable-fed, three-phase transformer where one of the phases is open (Fig. 3.11 *b*). Again, this may happen during energization or deenergization.

- One or two riser-pole fuses may blow leaving a transformer with one or two phases open. Single-phase re-closers may also cause this condition

It should be noted that these events do not always yield noticeable ferroresonance. Some utility personnel claim to have worked with underground cable systems for decades without seeing ferroresonance. System conditions that help increase the likelihood of ferroresonance include

- Higher distribution voltage levels, most notably 25- and 35-kV-classsystems
- Switching of lightly loaded and unloaded transformers
- Ungrounded transformer primary connections
- Very lengthy underground cable circuits
- Cable damage and manual switching during construction of underground cable systems

- Weak systems, i.e., low short-circuit currents
- Low-loss transformers
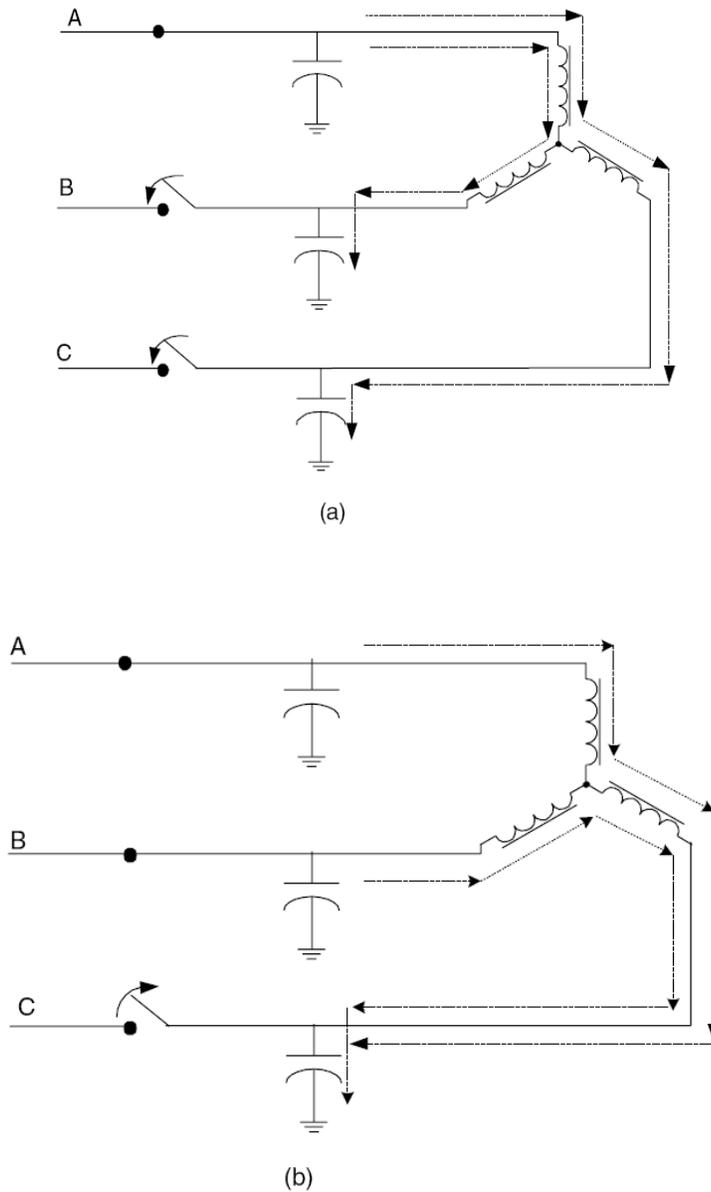- Three-phase systems with single-phase switching devices.



(a)



(b)

**Figure 3.11** Common system conditions where ferroresonance may occur: (*a*) one phase closed, (*b*) one phase open.

**Common indicators of ferroresonance are as follows.**

- Audible Noise.

- Overheating.

- High overvoltages and surge arrester failure.

- Flicker.

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