Inductance

In electromagnetism and electronics, **inductance** is the property of a conductor by which a change in current flowing through it induces (creates) a voltage (electromotive force) in both the conductor itself (self-inductance)[1] and in any nearby conductors (mutual inductance).[1]

These effects are derived from two fundamental observations of physics: First, that a steady current creates a steady magnetic field (Oersted's law),[2] and second, that a time-varying magnetic field induces voltage in nearby conductors (Faraday's law of induction).[3] According to Lenz's law,[4] a changing electric current through a circuit that contains inductance induces a proportional voltage, which opposes the change in current (self-inductance). The varying field in this circuit may also induce an e.m.f. in neighbouring circuits (mutual inductance).

The term 'inductance' was coined by Oliver Heaviside in February 1886.[5] It is customary to use the symbol L for inductance, in honour of the physicist Heinrich Lenz.[6][7] In the SI system the measurement unit for inductance is the henry (symbol: H), named in honor of the scientist who discovered inductance independently of, but not before, Faraday, Joseph Henry.[8]

1 Circuit analysis

To add inductance to a circuit, electrical or electronic components called inductors are used. Inductors are typically manufactured out of coils of wire, with this design delivering two circumstances, one, a concentration of the magnetic field, and two, a linking of the magnetic field into the circuit more than once.

The relationship between the self-inductance L of an electrical circuit (in henries), voltage, and current is

$$v(t) = L\frac{di}{dt}$$

Where $v(t)$ denotes the voltage in volts across the circuit, and $i(t)$ the current in amperes through the circuit. The formula implicitly states that a voltage is induced across an inductor, equal to the product of the inductor's inductance, and current's rate of change through the inductor.

All practical circuits have some inductance, which may provide beneficial or detrimental effects. For a tuned circuit, inductance is used to provide a frequency selective circuit. Practical inductors may be used to provide fil-

tering, or energy storage, in a given network. The inductance of a transmission line is one of the properties that determines its characteristic impedance; balancing the inductance and capacitance of cables is important for distortion-free telegraphy and telephony. The inductance of lengthy power transmission lines effectively results in a lessened delivery of AC power, due to the combination of inductance, coupled with transmission lines being spread across great distances. Sensitive circuits, such as microphone and computer network cables, may utilize special cabling construction, limiting the mutual inductance between signal circuits.

The generalization to the case of K electrical circuits with currents i_m and voltages v_m reads

$$v_m = \sum_{n=1}^{K} L_{m,n}\frac{di_n}{dt}.$$

Here, inductance L is a symmetric matrix. The diagonal coefficients $L_{m,m}$ are called coefficients of self-inductance, the off-diagonal elements are called coefficients of mutual inductance. The coefficients of inductance are constant, as long as no magnetizable material with nonlinear characteristics are involved. This is a direct consequence of the linearity of Maxwell's equations in the fields and the current density. The coefficients of inductance become functions of the currents in the nonlinear case, see nonlinear inductance.

2 Derivation from Faraday's law of inductance

The inductance equations above are a consequence of Maxwell's equations. There is a straightforward derivation in the important case of electrical circuits consisting of thin wires.

Consider a system of K wire loops, each with one or several wire turns. The flux linkage of loop m is given by

$$N_m \Phi_m = \sum_{n=1}^{K} L_{m,n} i_n.$$

Here N_m denotes the number of turns in loop m, Φ_m the magnetic flux through this loop, and $L_{m,n}$ are some constants. This equation follows from Ampere's law - mag-

netic fields and fluxes are linear functions of the currents. By Faraday's law of induction we have

$$v_m = N_m \frac{d\Phi_m}{dt} = \sum_{n=1}^{K} L_{m,n} \frac{di_n}{dt},$$

where v_m denotes the voltage induced in circuit m. This agrees with the definition of inductance above if the coefficients $L_{m,n}$ are identified with the coefficients of inductance. Because the total currents $N_n i_n$ contribute to Φ_m it also follows that $L_{m,n}$ is proportional to the product of turns $N_m N_n$.

3   Inductance and magnetic field energy

Multiplying the equation for v_m above with $i_m dt$ and summing over m gives the energy transferred to the system in the time interval dt,

$$\sum_m^K i_m v_m dt = \sum_{m,n=1}^{K} i_m L_{m,n} di_n \overset{!}{=} \sum_{n=1}^{K} \frac{\partial W(i)}{\partial i_n} di_n.$$

This must agree with the change of the magnetic field energy W caused by the currents.[9] The integrability condition

$$\frac{\partial^2 W}{\partial i_m \partial i_n} = \frac{\partial^2 W}{\partial i_n \partial i_m}$$

requires $L_{m,n}=L_{n,m}$. The inductance matrix $L_{m,n}$ thus is symmetric. The integral of the energy transfer is the magnetic field energy as a function of the currents,

$$W(i) = \tfrac{1}{2} \sum_{m,n=1}^{K} i_m L_{m,n} i_n.$$

This equation also is a direct consequence of the linearity of Maxwell's equations. It is helpful to associate changing electric currents with a build-up or decrease of magnetic field energy. The corresponding energy transfer requires or generates a voltage. A mechanical analogy in the K=1 case with magnetic field energy $(1/2)Li^2$ is a body with mass M, velocity u and kinetic energy $(1/2)Mu^2$. The rate of change of velocity (current) multiplied with mass (inductance) requires or generates a force (an electrical voltage).

4   Coupled inductors and mutual inductance

Further information: Coupling (electronics)
 Mutual inductance occurs when the change in cur-
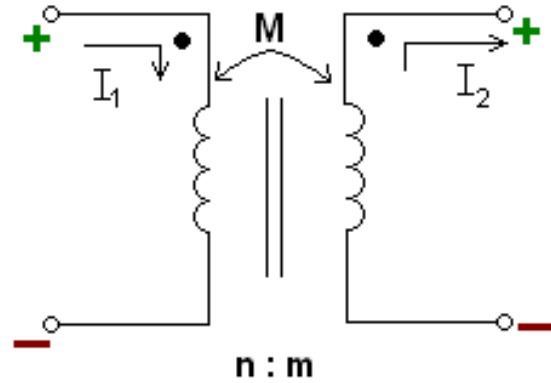
The circuit diagram representation of mutually coupled inductors. The two vertical lines between the inductors indicate a solid core that the wires of the inductor are wrapped around. "n:m" shows the ratio between the number of windings of the left inductor to windings of the right inductor. This picture also shows the dot convention.

rent in one inductor induces a voltage in another nearby inductor. It is important as the mechanism by which transformers work, but it can also cause unwanted coupling between conductors in a circuit.

The mutual inductance, M, is also a measure of the coupling between two inductors. The mutual inductance by circuit i on circuit j is given by the double integral *Neumann formula*, see calculation techniques

The mutual inductance also has the relationship:

$$M_{21} = N_1 N_2 P_{21}$$

where

> M_{21} is the mutual inductance, and the subscript specifies the relationship of the voltage induced in coil 2 due to the current in coil 1.
>
> N_1 is the number of turns in coil 1,
>
> N_2 is the number of turns in coil 2,
>
> P_{21} is the permeance of the space occupied by the flux.

The mutual inductance also has a relationship with the coupling coefficient. The coupling coefficient is always between 1 and 0, and is a convenient way to specify the relationship between a certain orientation of inductors with arbitrary inductance:

$$M = k\sqrt{L_1 L_2}$$

where

> k is the *coupling coefficient* and $0 \leq k \leq 1$,
>
> L_1 is the inductance of the first coil, and
>
> L_2 is the inductance of the second coil.

Once the mutual inductance, M, is determined from this factor, it can be used to predict the behavior of a circuit:

$$v_1 = L_1 \frac{di_1}{dt} - M \frac{di_2}{dt}$$

where

> v_1 is the voltage across the inductor of interest,
>
> L_1 is the inductance of the inductor of interest,
>
> di_1/dt is the derivative, with respect to time, of the current through the inductor of interest,
>
> di_2/dt is the derivative, with respect to time, of the current through the inductor that is coupled to the first inductor, and
>
> M is the mutual inductance.

The minus sign arises because of the sense the current i_2 has been defined in the diagram. With both currents defined going into the dots the sign of M will be positive (the equation would read with a plus sign instead).[10]

4.1 Matrix representation

The circuit can be described by any of the two-port network parameter matrix representations. The most direct is the z parameters which are given by

$$[\mathbf{z}] = s \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix}$$

where s is the complex frequency variable.

4.2 Equivalent circuit

Mutually coupled inductors can equivalently be represented by a T-circuit of inductors as shown. If the coupling is strong and the inductors are of unequal values then the series inductor on the step-down side may take on a negative value.

This can be analyzed as a two port network. With the output terminated with some arbitrary impedance, Z, the voltage gain, A_v is given by,
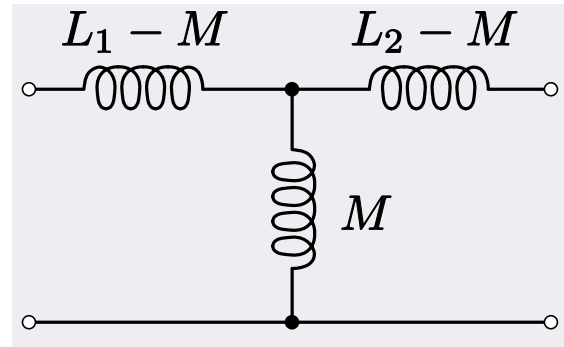
Equivalent circuit of mutually coupled inductors

$$A_v = \frac{sMZ}{s^2 L_1 L_2 - s^2 M^2 + sL_1 Z}$$

For tightly coupled inductors where $k = 1$ this reduces to

$$A_v = \sqrt{\frac{L_2}{L_1}}$$

which is independent of the load impedance. If the inductors are wound on the same core and with the same geometry, then this expression is equal to the turns ratio of the two inductors because inductance is proportional to the square of turns ratio.

The input impedance of the network is given by,

$$Z_{in} = \frac{s^2 L_1 L_2 - s^2 M + sL_1 Z}{sL_2 + Z}$$

For $k = 1$ this reduces to

$$Z_{in} = \frac{sL_1 Z}{sL_2 + Z}$$

Thus, the current gain, A_i is *not* independent of load unless the further condition

$$|sL_2| \gg |Z|$$

is met, in which case,

$$Z_{in} \approx \frac{L_1}{L_2} Z$$

and

$$A_i \approx \sqrt{\frac{L_1}{L_2}} = \frac{1}{A_v}$$

4.3   Tuned transformer

When either side of the transformer is a tuned circuit, the amount of mutual inductance between the two windings, together with the Q factor of the circuit, determine the shape of the frequency response curve. The tuned circuit together with the transformer load form an RLC circuit with a definite peak in the frequency response. When both sides of the transformer are tuned, it is described as double-tuned. The coupling of double-tuned circuits is described as loose-, critical-, or over-coupled depending on the value of k. When two tuned circuits are loosely coupled through mutual inductance, the bandwidth will be narrow. As the amount of mutual inductance increases, the bandwidth continues to grow. When the mutual inductance is increased beyond a critical point, the peak in the response curve begins to drop, and the center frequency will be attenuated more strongly than its direct sidebands. This is known as overcoupling.

4.4   Ideal Transformers

When $k = 1$, the inductor is referred to as being closely coupled. If in addition, the self-inductances go to infinity, the inductor becomes an ideal transformer. In this case the voltages, currents, and number of turns can be related in the following way:

$$V_s = \frac{N_s}{N_p} V_p$$

where

V_s is the voltage across the secondary inductor,

V_p is the voltage across the primary inductor (the one connected to a power source),

N_s is the number of turns in the secondary inductor, and

N_p is the number of turns in the primary inductor.

Conversely the current:

$$I_s = \frac{N_p}{N_s} I_p$$

where

I_s is the current through the secondary inductor,

I_p is the current through the primary inductor (the one connected to a power source),

N_s is the number of turns in the secondary inductor, and

N_p is the number of turns in the primary inductor.

Note that the power through one inductor is the same as the power through the other. Also note that these equations don't work if both inductors are forced (with power sources).

5   Calculation techniques

In the most general case, inductance can be calculated from Maxwell's equations. Many important cases can be solved using simplifications. Where high frequency currents are considered, with skin effect, the surface current densities and magnetic field may be obtained by solving the Laplace equation. Where the conductors are thin wires, self-inductance still depends on the wire radius and the distribution of the current in the wire. This current distribution is approximately constant (on the surface or in the volume of the wire) for a wire radius much smaller than other length scales.

5.1   Mutual inductance of two wire loops

The mutual inductance by a filamentary circuit m on a filamentary circuit n is given by the double integral *Neumann formula*[11]

$$L_{m,n} = \frac{\mu_0}{4\pi} \oint_{C_m} \oint_{C_n} \frac{\mathbf{dx}_m \cdot \mathbf{dx}_n}{|\mathbf{x}_m - \mathbf{x}_n|}$$

The symbol μ_0 denotes the magnetic constant ($4\pi \times 10^{-7}$ H/m), Cm and Cn are the curves spanned by the wires. See a derivation of this equation.

5.2   Self-inductance of a wire loop

Formally the self-inductance of a wire loop would be given by the above equation with $m = n$. The problem, however, is that $1/|x\text{-}x'|$ now becomes infinite, making it necessary to take the finite wire radius a and the distribution of the current in the wire into account. There remain the contribution from the integral over all points with $|x\text{-}x'| > a/2$ and a correction term,[12]

$$L = \left(\frac{\mu_0}{4\pi} \oint_C \oint_{C'} \frac{\mathbf{dx} \cdot \mathbf{dx'}}{|\mathbf{x} - \mathbf{x'}|} \right)_{|\mathbf{x}-\mathbf{x'}|>a/2} + \frac{\mu_0}{4\pi} lY + O\left(\mu_0 a\right).$$

Here a and l denote radius and length of the wire, and Y is a constant that depends on the distribution of the current in the wire: $Y = 0$ when the current flows in the surface of the wire (skin effect), $Y = 1/2$ when the current is homogeneous across the wire. This approximation is accurate when the wires are long compared to their cross-sectional dimensions.

5.3 Method of images

In some cases different current distributions generate the same magnetic field in some section of space. This fact may be used to relate self inductances (method of images). As an example consider the two systems:

- A wire at distance *d/2* in front of a perfectly conducting wall (which is the return)

- Two parallel wires at distance *d*, with opposite current

The magnetic field of the two systems coincides (in a half space). The magnetic field energy and the inductance of the second system thus are twice as large as that of the first system.

5.4 Relation between inductance and capacitance

Inductance per length L' and capacitance per length C' are related to each other in the special case of transmission lines consisting of two parallel perfect conductors of arbitrary but constant cross section,[13]

$$L'C' = \varepsilon\mu.$$

Here ε and μ denote dielectric constant and magnetic permeability of the medium the conductors are embedded in. There is no electric and no magnetic field inside the conductors (complete skin effect, high frequency). Current flows down on one line and returns on the other. Signals will propagate along the transmission line at the speed of electromagnetic radiation in the non-conductive medium enveloping the conductors.

6 Self-inductance of simple electrical circuits in air

The self-inductance of many types of electrical circuits can be given in closed form. Examples are listed in the table.

The symbol μ_0 denotes the magnetic constant ($4\pi\times10^{-7}$ H/m). For high frequencies the electric current flows in the conductor surface (skin effect), and depending on the geometry it sometimes is necessary to distinguish low and high frequency inductances. This is the purpose of the constant Y: $Y = 0$ when the current is uniformly distributed over the surface of the wire (skin effect), $Y = 1/2$ when the current is uniformly distributed over the cross section of the wire. In the high frequency case, if conductors approach each other, an additional screening current flows in their surface, and expressions containing Y become invalid.

7 Inductance with physical symmetry

7.1 Inductance of a solenoid

A solenoid is a long, thin coil, i.e. a coil whose length is much greater than the diameter. Under these conditions, and without any magnetic material used, the magnetic flux density B within the coil is practically constant and is given by

$$B = \mu_0 Ni/l$$

where μ_0 is the magnetic constant, N the number of turns, i the current and l the length of the coil. Ignoring end effects, the total magnetic flux through the coil is obtained by multiplying the flux density B by the cross-section area A :

$$\Phi = \mu_0 NiA/l,$$

When this is combined with the definition of inductance,

$$L = N\Phi/i$$

it follows that the inductance of a solenoid is given by:

$$L = \mu_0 N^2 A/l.$$

A table of inductance for short solenoids of various diameter to length ratios has been calculated by Dellinger, Whittmore, and Ould[17]

This, and the inductance of more complicated shapes, can be derived from Maxwell's equations. For rigid air-core coils, inductance is a function of coil geometry and number of turns, and is independent of current.

Similar analysis applies to a solenoid with a magnetic core, but only if the length of the coil is much greater than the product of the relative permeability of the magnetic core and the diameter. That limits the simple analysis to low-permeability cores, or extremely long thin solenoids. Although rarely useful, the equations are,

$$B = \mu_0 \mu_r Ni/l$$

where μ_r the relative permeability of the material within the solenoid,

$$\Phi = \mu_0 \mu_r NiA/l,$$

from which it follows that the inductance of a solenoid is given by:

$$L = \mu_0 \mu_r N^2 A / l.$$

where N is squared because of the definition of inductance.

Note that since the permeability of ferromagnetic materials changes with applied magnetic flux, the inductance of a coil with a ferromagnetic core will generally vary with current.

7.2   Inductance of a coaxial line

Let the inner conductor have radius r_i and permeability μ_i , let the dielectric between the inner and outer conductor have permeability μ_d , and let the outer conductor have inner radius r_{o1} , outer radius r_{o2} , and permeability μ_o . Assume that a DC current I flows in opposite directions in the two conductors, with uniform current density. The magnetic field generated by these currents points in the azimuthal direction and is a function of radius r ; it can be computed using Ampère's law:

$$0 \leq r \leq r_i : B(r) = \frac{\mu_i I r}{2\pi r_i^2}$$

$$r_i \leq r \leq r_{o1} : B(r) = \frac{\mu_d I}{2\pi r}$$

$$r_{o1} \leq r \leq r_{o2} : B(r) = \frac{\mu_o I}{2\pi r} \left(\frac{r_{o2}^2 - r^2}{r_{o2}^2 - r_{o1}^2} \right)$$

The flux per length l in the region between the conductors can be computed by drawing a surface containing the axis:

$$\frac{d\phi_d}{dl} = \int_{r_i}^{r_{o1}} B(r) dr = \frac{\mu_d I}{2\pi} \ln \frac{r_{o1}}{r_i}$$

Inside the conductors, L can be computed by equating the energy stored in an inductor, $\frac{1}{2} L I^2$, with the energy stored in the magnetic field:

$$\frac{1}{2} L I^2 = \int_V \frac{B^2}{2\mu} dV$$

For a cylindrical geometry with no l dependence, the energy per unit length is

$$\frac{1}{2} L' I^2 = \int_{r_1}^{r_2} \frac{B^2}{2\mu} 2\pi r \, dr$$

where L' is the inductance per unit length. For the inner conductor, the integral on the right-hand-side is $\frac{\mu_i I^2}{16\pi}$; for the outer conductor it is

$$\frac{\mu_o I^2}{4\pi} \left(\frac{r_{o2}^2}{r_{o2}^2 - r_{o1}^2} \right)^2 \ln \frac{r_{o2}}{r_{o1}} - \frac{\mu_o I^2}{8\pi} \left(\frac{r_{o2}^2}{r_{o2}^2 - r_{o1}^2} \right) - \frac{\mu_o I^2}{16\pi}$$

Solving for L' and summing the terms for each region together gives a total inductance per unit length of:

$$L' = \frac{\mu_i}{8\pi} + \frac{\mu_d}{2\pi} \ln \frac{r_{o1}}{r_i} + \frac{\mu_o}{2\pi} \left(\frac{r_{o2}^2}{r_{o2}^2 - r_{o1}^2} \right)^2 \ln \frac{r_{o2}}{r_{o1}} - \frac{\mu_o}{4\pi} \left(\frac{r_{o2}^2}{r_{o2}^2 - r_{o1}^2} \right) - \frac{\mu_o}{8\pi}$$

However, for a typical coaxial line application we are interested in passing (non-DC) signals at frequencies for which the resistive skin effect cannot be neglected. In most cases, the inner and outer conductor terms are negligible, in which case one may approximate

$$L' = \frac{dL}{dl} \approx \frac{\mu_d}{2\pi} \ln \frac{r_{o1}}{r_i}$$

8   Phasor circuit analysis and impedance

If signals of current and voltage are sine, using phasors, the equivalent impedance of an inductance is given by:

$$Z_L = V / I = j\omega L$$

where

> j is the imaginary unit,
>
> L is the inductance,
>
> $\omega = 2\pi f$ is the angular frequency,
>
> f is the frequency and
>
> $\omega L = XL$ is the inductive reactance.

9   Nonlinear inductance

Many inductors make use of magnetic materials. These materials over a large enough range exhibit a nonlinear permeability with such effects as saturation. In turn, the saturation makes the resulting inductance a function of the applied current. Faraday's Law still holds but inductance is ambiguous and is different whether you are calculating circuit parameters or magnetic fluxes.

The secant or large-signal inductance is used in flux calculations. It is defined as:

$$L_s(i) \stackrel{\text{def}}{=} \frac{N\Phi}{i} = \frac{\Lambda}{i}$$

The differential or small-signal inductance, on the other hand, is used in calculating voltage. It is defined as:

$$L_d(i) \stackrel{\text{def}}{=} \frac{d(N\Phi)}{di} = \frac{d\Lambda}{di}$$

The circuit voltage for a nonlinear inductor is obtained via the differential inductance as shown by Faraday's Law and the chain rule of calculus.

$$v(t) = \frac{d\Lambda}{dt} = \frac{d\Lambda}{di}\frac{di}{dt} = L_d(i)\frac{di}{dt}$$

There are similar definitions for nonlinear mutual inductances.

10   See also

- Alternating current

- Dot convention

- Eddy current

- Electromagnetic induction

- Electricity

- Faraday's law of induction

- Gyrator

- Hydraulic analogy

- Inductor

- Leakage inductance

- LC circuit

- Magnetomotive force (MMF)

- RLC circuit

- RL circuit

- SI electromagnetism units

- Solenoid

- Transformer

- Kinetic inductance

- LCR meter

11   References

[1] Sears and Zemansky 1964:743

[2] Sears and Zemansksy 1964:671

[3] Sears and Zemansky 1964:671 -- "The work of Oersted thus demonstrated that magnetic effects could be produced by moving electric charges, and that of Faraday and Henry that currents could be produced by moving magnets."

[4] Sears and Zemansky 1964:731 -- "The direction of an induced current is such as to oppose the cause producing it".

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13   External links

- *Clemson Vehicular Electronics Laboratory: Inductance Calculator*

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14.1 Text

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