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We know that electric currents can be induced in closed coils when subjected to varying magnetic fields. This phenomenon of inducing current or emf in a coil by changing magnetic fields is called the electromagnetic induction or EMI.We also know that if a current flows through any coil, whether the current is increasing, or decreasing, the coil opposes the change in the current's strength passing through it. This means supplying varying current is necessary.So, if we use two coils in place of one, what type of phenomenon will occur here?Well, mutual inductance takes place between these two coils. About the Concept of Mutual InductanceTo understand this concept, let us take two coils P and S (Distinct coils) and keep them side-by-side. We connect one coil to the switch, and the other to a galvanometer. As soon as a varying current is generated in coil P, automatically current induces in the coil S.P coil is known as the primary coil, and the S coil in which we see the deflection is the secondary coil.So What Happens Next?Well, the varying current in the P coil generates varying magnetic field lines that pass through both the coils.This means increasing the current; the magnetic field lines increase because of which the flux at the secondary coil increases.When this flux increases, an induced EMF is generated in the coil because of which an induced current starts flowing in it. Therefore, the galvanometer shows a deflection.To find the direction of the magnetic field lines, we curl our fingers of our right hand around the wire, the direction in which the thumb points, is the direction of the magnetic field.We can see that the magnetic field lines are in the direction of the current. If these lines change (because of the changing current), the flux in the secondary coil changes because of which an induced emf and the induced current generates in it. Mutual Induction DerivationWe know that on increasing the current in the primary coil, the flux in the secondary coil increases. I.e., (ϕ2)T ∝ I(Image will be uploaded Soon)We are not sure of the number of turns in the S coil. So, to calculate the total flux, we have taken the subscript T in (ϕ2)T.On removing the sign of proportionality constant, we get,(ϕ2)T = MIWhere M is the constant of proportionality and is called the coefficient of mutual induction or mutual inductance of two coils.The unit of mutual inductance is:M = (ϕ2)T /I = \[\frac{Weber}{Ampere}\] = \[\frac{Volt-sec}{Ampere}\] = Henry.∴ The unit of M is Henry.If I = 1, (ϕ2)T = M x 1 M = (ϕ2)TThus the coefficient of mutual inductance of two coils is equal to the amount of flux that generates in one coil because of the current flow in the primary coil.M doesn't depend on (ϕ2)T, and I because it is a constant term. However, it depends upon the following factors:Geometry (shape) of the coils, Their separation (or the radius of the coils), The orientation (coils kept parallel or inclined at some angle), andThe medium in which we keep these coils.We know that an EMF is induced in the secondary coil. Now we will apply Faraday's law here:e2 = - d(ϕ2)T/dt = - d(MI1)/dt(Its because the flux of S coil, i.e., (ϕ2)T depends on the current (I1) in the P coil)e2 = - M dI1/dtIf dI1/dt = 1, then M = - e2EMF in the secondary coil generates only when there is a change in the current I1.∴The coefficient of mutual inductance of two coils is equal to the induced emf in the S coil when the rate of change of current in the P coil is unity. Important Formulas in Mutual Induction1. Coefficient of Coupling (K)The coefficient of coupling in two coils is a measure of the coupling between the two coils. It is given by K = \[\frac{M}{\sqrt{L_{1}L_{2}}}\]Where L1 and L2 are coefficients of the self-inductance of the two coils. The value of K is always < 1. If the two coils are arranged in series, then their K = 1, then we can show thatL = L1 + L2 + 2M (When current in two coils is in the same direction), andL = L1 + L2 - 2M (When current in two coils in the opposite directions).2. Mutual Inductance of Two Long Coaxial Solenoids (S1 and S2)M = \[\frac{{\mu_{0}N_{1}N_{2}A}}{l}\]Where μ0 = Magnetic constant,N1 and N2 = Total number of turns in a solenoid S1, and S2, respectively, l = Length of the longer solenoid, andA = πr2= Cross-sectional area of the inner solenoid.Application of Mutual InductanceMutual induction is the basic operating principle for the following:TransformersMotors GeneratorsWhat is Inductance?In the field of electronics and electromagnetic, inductance is a key notion that describes a conductor's tendency to oppose current flow. A magnetic field is created across the conductor by the current flow. The field strength is determined by the size of the current and changes as the current changes.Types of InductanceThere are two main types of inductance:Self InductanceMutual InductanceHere we will study about InductionMutual InductanceWhen two coils are brought near together, the magnetic field in one of the coils directs to connect with the other coil, according to the definition of mutual induction. This leads to voltage development in the second coil. A mutual inductance property describes the situation in which one coil influences or alters the voltage and current values in the other coil.Leakage and stray inductance are two negative consequences of mutual inductance. Through the process of electromagnetic induction, when they are released from one coil, they alter the functionality of another element.It has a fairly simple theory that may be grasped by employing two or more coils. In the 18th century, an American scientist named Joseph Henry characterized it. One of the qualities of the coil or conductor utilized in the circuit is this. If the current in one coil fluctuates with time, the EMF will induce in another coil, according to the property inductance. The transformer, for example, is a fundamental example of mutual inductance. The fundamental disadvantage of mutual inductance is that leakage of one coil's inductance might cause the operation of another coil using electromagnetic induction to be disrupted. Electrical screening is essential to reduce leakage.Mutual Inductance FormulaThe formula of two coils is given asM = \[\frac{\mu_{0}N_{1}N_{2}A}{l}\]Where μ0= permeability of free space = 4π10-2μ = permeability of the soft iron coreN1= turns of coil 1N2= turns of coil 2A= cross-sectional area in m2L = length of the coil in metersThe unit of mutual inductance is kg. m2.s-2.A-2The amount of inductance produces the voltage of one volt due to the rate of change of current of 1 Ampere/second.Joseph Henry, a scientist from the United States, coined the term to describe the phenomenon of two coils. Figure 1. Setup to understand the concept of Mutual Inductance. Definition of Mutual Inductance Mutual Inductance is defined as the property due to which the e m f is induced in the other coil due to change in current through one coil produces an emf in the other coil placed nearby, by induction. Two Coils When the current in L1 changes with time, then the magnetic field lines also changes magnetically coupled coils C1 and C2 in Fig. 1, are said to have mutual inductance. It is denoted by M and measured in Henry. The expression for mutual inductance is, \[M=\frac{{{N}_{2}}{{\phi }_{2}}}{{{I}_{1}}}\] Or, \[M=\frac{{{N}_{1}}\times {{\phi }_{1}}}{{{I}_{2}}}\] Where N1 and N2 are the number of turns of coils C1 and C2. I1 and I2 are the currents flowing through them. ϕ1 is the flux produced by I1 in C1 and is the flux ϕ2 produced by I2 in C2. Setup for Mutual Inductance The setup to understand the concept of mutually induced e.m.f is as shown in Fig. 1. Two coils C1 and C2 are placed near each other. Coil C1 consists of N1 turns and coil C2 consists of N2 number of turns. A switch, battery and a variable resistance R are connected in the circuit consisting of coil C1. Whereas, a galvanometer is connected to coil C2. This galvanometer is connected to sense the current induced in coil C2. Description : Due to the battery a current I1 starts flowing through coil C1. This current can be changed by changing the value of resistance R. Due to current I1 flowing through coil C1, flux is produced, which is denoted by ϕ1. A part of this flux completes its path through coil C2 as shown in Fig. 1. This flux is called as the mutual flux. If we change current I1 through coil C1 by changing R, then flux ϕ1 will change. This will change the mutual flux ϕ2. According to the Faraday's laws there will be induced e.m.f. in coil C2. Due to this emf, current I2 will start flowing through coil C2 which is indicated by the galvanometer "G". Thus if the flux produced by one coil gets linked with another coil, and due to the change in this flux produced by the coil C1 if there is induced emf in the second coil then such an emf is known as mutually induced emf. The mutually induced emf in coil C2 will exist as long as the value of current through coil C1 i.e. I1 is changing with respect to time. Formula for Mutual Inductance : The expression for mutual inductance is as follows: \[M=\frac{{{N}_{1}}{{N}_{2}}{{\mu }_{0}}{{\mu }_{r1}}{{a}_{1}}}{{{l}_{1}}}\]\ \[M=\frac{{{N}_{1}}{{N}_{2}}{{\mu }_{0}}{{\mu }_{r2}}{{a}_{2}}}{{{l}_{2}}}\] Where N1, N2 = Number of turns of coils C1 and C2 a1, a2 = Cross sectional areas. l1, l2 = Lengths of the coils. Coefficient of Coupling (K) : The two expressions for the mutual inductance are, \[M=\frac{{{N}_{1}}{{K}_{2}}{{\phi }_{1}}}{{{I}_{1}}}...(1)\] And, \[M=\frac{{{N}_{1}}{{K}_{2}}{{\phi }_{2}}}{{{I}_{2}}}....(2)\] Multiply Equations (1) and (2) to get, \[{{M}^{2}}=\frac{{{N}_{1}}{{N}_{2}}{{K}_{1}}{{K}_{2}}{{\phi }_{1}}{{\phi }_{2}}}{{{I}_{1}}{{I}_{2}}}\] Rearrange this expression as follows : \[{{M}^{2}}={{K}_{1}}.{{K}_{2}}.\left( \frac{{{N}_{1}}{{\phi }_{1}}}{{{I}_{1}}} \right)\left( \frac{{{N}_{2}}{{\phi }_{2}}}{{{I}_{2}}} \right)...(3)\] But, \[\left( \frac{{{N}_{1}}{{\phi }_{1}}}{{{I}_{1}}} \right)={{L}_{1}}\] i.e. self inductance of coil C1. And, \[\left( \frac{{{N}_{2}}{{\phi }_{2}}}{{{I}_{2}}} \right)={{L}_{2}}\] i.e. the self inductance of coil C2. Substituting these values into Equation (3) we get, \[{{M}^{2}}={{K}_{1}}.{{K}_{2}}.{{L}_{1}}.{{L}_{2}}\] \[M=\sqrt{{{K}_{1}}.{{K}_{2}}}.\sqrt{{{L}_{1}}.{{L}_{2}}}\] \[M=K\sqrt{{{L}_{1}}.{{L}_{2}}}\] Where, \[K=\sqrt{{{K}_{1}}.{{K}_{2}}}\] And K is called as the coefficient of coupling. Mathematical expression for coefficient of coupling is : \[K=\frac{M}{\sqrt{{{L}_{1}}.{{L}_{2}}}}\] Definition : From this expression, we can define the coefficient of coupling K as the ratio of actual mutual inductance (M) present between the coils C1 and C2 to the maximum value of M. However, \[{{M}_{\max }}=\sqrt{{{L}_{1}}.{{L}_{2}}}\] \[K=\frac{M}{{{M}_{\max }}}\] The maximum value of K is 1 which represents the coupling of all the flux produced by one with the other one. Corresponding to K = 1 the value of the mutual inductance will be maximum and it is given by, \[{{M}_{\max }}=\sqrt{{{L}_{1}}.{{L}_{2}}}\] Definition : Thus, the coefficient of mutual inductance is defined as the property which is responsible for the induced emf in one coil due to change in current flowing through some other coil placed nearby. Tight coupling and loose coupling : The coupling between the two coils is said to be a tight coupling if K = 1 and the coupling is called as the loose coupling if K is less than one. The coefficient of coupling is also called as Magnetic Coupling Coefficient. In 1831, Michael Faraday explained the theory of electromagnetic induction scientifically. The term inductance is, the capacity of the conductor to oppose the current flowing through it and induces emf. From Faraday's laws of induction, an electromotive force (EMF) or voltage is induced in the conductor due to the change in the magnetic field through the circuit. This process is stated as electromagnetic induction. The induced voltage opposes the rate of change of current. This is known as Lenz's law and the induced voltage is called back EMF. Inductance is divided into two types. They are, Self-inductance and mutual inductance. This article is all about the mutual inductance of two coils or conductors. What is Mutual Inductance? Definition: The mutual inductance of two coils is defined as the emf induced due to the magnetic field in one coil opposes the change of current and voltage in another coil. That means the two coils are magnetically linked together due to the change in magnetic flux. The magnetic field or flux of one coil links with another coil. This is denoted by M. The current flowing in one coil induces the voltage in the another coil due to the change in magnetic flux. The amount of magnetic flux linked with the two coils is directly proportional to the mutual inductance and change in current. Mutual Inductance Theory Its theory is very simple and it can be understood by using two or more coils. It was described by an American scientist Joseph Henry in the 18th century. It is referred to as one of the properties of the coil or conductor used in the circuit. The property inductance is, if the current in one coil changes with time, then the EMF will induce in another coil. Oliver Heaviside introduced the term inductance in the year 1886. The property of mutual inductance is the working principle of many electrical components that run with the magnetic field. For example, the transformer is a basic example of mutual inductance. The main drawback of the mutual inductance is, leakage of the inductance of one coil can interrupt the operation of another coil utilizing electromagnetic induction. To reduce the leakage, electrical screening is required The positioning of two coils in the circuit decides the amount of mutual inductance that links with one to the other coil. Mutual Inductance Formula The formula of two coils is given as M= ( μ0.μr. N1. N2. A) / L Where μ0= permeability of free space = 4π10-2 μ = permeability of the soft iron core N1= turns of coil 1 N2= turns of coil 2 A= cross-sectional area in m2 L = length of the coil in meters Unit of Mutual Inductance The unit of mutual inductance is kg. m2.s-2.A-2 The amount of inductance produces the voltage of one volt due to the rate of change of current of 1Ampere/second. The SI unit of mutual inductance is Henry. It is taken from the American scientist Joseph Henry, who explained the phenomenon of two coils. The Dimension of Mutual Inductance When two or more coils are linked together magnetically with the same magnetic flux, then the voltage induced in one coil is proportional to the rate of change of current in another coil. This phenomenon is referred to as mutual inductance. Consider the total inductance between the two coils be L since M = √(L1L2) = L The dimension of this can be defined as the ratio of potential difference to the rate of change of current. It is given as Since M = √L1L2 = L L = € / (dI / dt) Where € = induced EMF = work done / electric charge with respect to time = M. L2. T-2/ IT = M.L2.T-3. I-1 or € = M. L-2 . T-3. A-1 (Since I = A) For inductance, ϕ = LI L = ϕ / A=( B. L2 ) / A Where B = magnetic field =( MLT-2) /LT-1AT = MT-2A-1 Magnetic flux ϕ= BL2 = MT-2L2A-1 substitute value of B and ϕ is above formula L L= MT-2L2A-2 The dimension of mutual inductance when L1 and L2 are the same is given as M = L /(T-2L2.A-2) M = LT2L2.A-2 Derivation Follow the process to get the mutual inductance derivation. The ratio of EMF induced in one coil and the rate of change of current in another coil is mutual inductance. Consider the two coils L1 and L2 as shown in the figure below. Two Coils When the current in L1 changes with time, then the magnetic field also changes with time and changes the magnetic flux linked with the second coil L2. Due to this magnetic flux change, an EMF is induced in the first coil L1. Also, the rate of change of current in the first coil induces EMF in the second coil. Hence EMF is induced in the two coils L1 and L2. This is given as €= M (dI1 / dt) M = € / ( dI1 / dt) . … .. Eq 1 If € = 1 volt and dI1 / dt = 1Amp, then M = 1 Henry Also, The rate of change of current in one coil produces the magnetic flux in the first coil and associates with the second coil. Then from the Faraday's laws of electromagnetic induction (induced voltage is directly proportional to the rate of change of magnetic flux linked) in the second coil, induced EMF is given as €= M / ( dI1 / dt) = d (MI1) / dt… .. Eq 2 €= N2 ( dϕ12 / dt) = d ( N2ϕ12) / dt…eq 3 By equating eq 2 and 3 MI1 = N2ϕ12 M= (N2ϕ12) / I1 Henry Where M = mutual inductance €= mutual inductance EMF N2 = no of turns in first coil L1 I1 = current in the first coil ϕ12 = magnetic flux linked in two coils. The mutual inductance between the two coils depends on no of turns on the second coil or adjacent coil and the area of the cross-section Distance between two coils. The EMF induced in the first coil due to the rate of change of flux is given as, E = -M12 ( dI1 / dt) The minus sign indicates opposition to the rate of change of current in the first coil when EMF is induced. Mutual Inductance of Two Coils The mutual inductance of two coils can be increased by placing them on a soft iron core or by increasing the no of turns of the two coils. Unity coupling exists between the two coils when they are tightly wound on a soft iron core. The leakage of flux would be small. If the distance between the two coils is short, then the magnetic flux produced in the first coil interacts with all the turns of the second coil, which results in large EMF and mutual inductance. Mutual Inductance of Two Coils If the two coils are farther and apart from each other at different angles, then the induced magnetic flux in the first coil generates weak or small EMF in the second coil. Hence the mutual inductance will also be small. Two Coils Away from Each Other Thus the value of this mainly depends on the positioning and spacing of two coils on a soft iron core. Consider the figure, which shows that the two coils are tightly wound one on the top of the soft iron core. Coils are Tightly Wound The change of current in the first coil produces a magnetic field and passes the magnetic lines through the second coil, which is used to calculate mutual inductance. The mutual inductance of two coils is given as M12 = (N2ϕ12) / I1 M21= (N1ϕ21) / I2 Where M12=mutual inductance of the first coil to second coil M21= mutual inductance of the second coil to the fist coil N2=turns of the second coil N1=turns of the first coil I1=current flowing around the first coil I2=current flowing around the second coil. If the flux linked with the L1 and L2 is the same as the current flowing around them, then the mutual inductance of the first coil to the second coil is given as M21 The mutual inductance of two coils can be defined as M12= M21 = M So, two coils mainly depend on the size, turns, position, and spacing between the two coils. The self-inductance of the first coil is L1 = (μ0.μr.N12.A) / L The self-inductance of the second coils is L2 = (μ0.μr.N2.A) / L Cross-multiply the above two formulae Then the mutual inductance of two coils, which exists between them is given as M2 = L1. L2 M=√(L1.L2) Henry The above equation gives magnetic flux= 0 100% magnetic coupling between L1 and L2 Coupling Coefficient The fraction of magnetic flux linked with the two coils to the total magnetic flux between the coils is known as the coupling coefficient and it is denoted by 'k'. The coupling coefficient is defined as the ratio of the open circuit to the actual voltage ratio and the ratio of magnetic flux obtained in both the coils. Since the magnetic flux of one coil links with another coil. The coupling coefficient specifies the inductance of an inductor. If the coefficient coupling k = 1, then the two coils are coupled together tightly. So, all the lines of magnetic flux of one coil cut all the turns of another coil. Hence the mutual inductance is the geometric mean of individual inductances of two coils. If the inductances of two coils are the same (L1=L2), then the mutual inductance between the two coils is equal to the inductance of a single coil. That means, M= √(L1 . L2) = L where L = inductance of a single coil. Coupling Factor between Coils The coupling factor between coils can be represented as 0 and 1 If the coupling factor is 1, then there is no inductive coupling between the coils. If the coupling factor is 0, then there is a maximum or full inductive coupling between the coils. The inductive coupling is represented in 0 and 1, but not in percentages. For example, if k= 1 then the two coils are coupled perfectly If k>0.5, then the two coils are coupled tightly If k r2 placed in air is.Sol. The magnetic field, due to the larger coil at its centre isB=2r1μ0IThe flux through the inner coil isϕ=B×π×r22=2r1μ0I×πr22ϕ=MIM=2r1μ0πr22Q-2. The mutual inductance coefficient between the primary and secondary windings of a transformer 5H. Calculate the induced emf in the secondary when 3 A current in the primary is cutoff in 2.5 x 10−4 s.Sol.є2=−MdtdI1=−5×2.5×10−43=−5×3×4000=−6×104 VQ-3. List the factors that affect Mutual inductance.Sol.Number of turns of both the coils primary(N1) and secondary( N2).Area of cross - section of the coils.Magnetic Permeability of medium between the coils (μr)Nature of material on which two coils are wound.Distance between two coils.Orientation between primary and secondary coil.Coupling factor (K) between two coils(Primary and Secondary).Q-4.Write the dimensional formula for mutual induction?Sol. M = −dtdI1є2 , the dimensional formula is [M1L2T-2A-2]Q-5. A conducting wire with 100 turns is wound around the central region of a solenoid. The solenoid itself is 100 cm in length and has a radius of 2 cm, with 600 turns of wire. Calculate the mutual inductance between these two coils.Sol. M=lμ0N1N2AN1 = 600, N2 = 100, L = 100 cm = 1m, r = 2cm = 2 x 10−2m A=πr2=3.14×4×10−4 m2M=4×3.14×10−7×600×100×3.14×4×10−4M=14×3.14×10−7×600×100×3.14×4×10−4=9.45×10−5H Mutual inductance occurs when a change in current in one coil induces voltage in a nearby coil through the interaction of their magnetic fields.Mutual InductanceMutual inductance is a fundamental concept in electromagnetism, describing the interaction between two electrical circuits or coils. It occurs when a change in current in one coil, called the primary coil, induces a voltage in another nearby coil, known as the secondary coil, through the magnetic field generated by the primary coil.Understanding Mutual InductanceWhen a current flows through a coil, it creates a magnetic field around it. If another coil is placed within the vicinity of the first coil, the magnetic field generated by the first coil will interact with the second coil. This interaction induces a voltage in the second coil, which is the basis of mutual inductance. The amount of voltage induced in the second coil depends on the rate of change of the magnetic field and the number of turns in the coil.Factors Affecting Mutual InductanceSeveral factors influence the mutual inductance between two coils, including:Distance between coils: As the distance between the coils increases, the mutual inductance decreases, as the magnetic field from the primary coil has less effect on the secondary coil.Number of turns: The more turns in the coils, the greater the mutual inductance.Coil orientation: The mutual inductance is maximized when the coils are aligned with their axes parallel to each other and minimized when their axes are perpendicular.Core material: The presence of a magnetic material, such as iron, in the core of the coils increases the mutual inductance by concentrating the magnetic field lines.Applications of Mutual InductanceMutual inductance plays a critical role in various electrical devices and applications, such as:Transformers: Mutual inductance is the fundamental principle behind transformers, which are used to transfer electrical energy between circuits through magnetic fields. Transformers use mutual inductance to step up or step down voltage levels.Inductive sensors: Devices like metal detectors and proximity sensors utilize mutual inductance to detect changes in the magnetic field caused by nearby objects.Wireless power transfer: Mutual inductance is a key factor in inductive coupling, which enables wireless power transfer between coils without physical contact. According to Faraday's law, a current-carrying wire produces a magnetic field. If the current changes with time, the magnetic field will also change. Suppose the wire is wound into a coil and another coil is brought closer to it. Then, the changing magnetic field in the first coil will induce an emf (electromotive force) in the second. This phenomenon is known as mutual induction. The property that links the two coils by a common magnetic field is known as mutual inductance.The induced emf will cause a current to flow in the second coil. Lenz's law determines the direction of the induced current. This direction is such that it will oppose the change of current in the first coil. Now, suppose both the coils carry current. Then, emf will be induced in each coil due to changing current in the other. Hence, mutual inductance can also be defined as the property that describes the effect on one coil's magnetic field with another coil's magnetic field. Mutual Inductance Suppose two coils are placed next to each other. The first coil has N1 turns and carries current I1 giving rise to magnetic field B1. The second coil has N2 turns. Since the two coils are close, some of the magnetic field lines through coil 1 will also pass through coil 2. Let φ21 denote the magnetic flux through one turn of coil 2 due to I1. According to Faraday's law, changing the current I1 changes the magnetic flux φ21. It results in an induced emf ε21 given by the following formula. \[ \epsilon = -N_2 \frac{\Delta \phi_{21}}{\Delta t} \] The rate of magnetic flux change in coil 2 is proportional to the rate of current change in coil 1. Therefore, \[ N_2 \frac{\Delta \phi_{21}}{\Delta t} \propto \frac{\Delta I_1}{\Delta t} \\ \Rightarrow N_2 \frac{\Delta \phi_{21}}{\Delta t} = M_{21} \frac{\Delta I_1}{\Delta t} \] The constant of proportionality M21 is the mutual inductance. It has the SI unit of Henry or H, named after American scientist Joseph Henry who discovered electromagnetic induction. 1 H = 1 Wb/A or 1 T·m2/A or 1 V·s/A. Rewriting the induced emf equation \[ \epsilon_{21} = -M_{21}\frac{\Delta I_1}{\Delta t} \\ \Rightarrow M_{21} = \frac{\epsilon_{21}}{\left| \frac{\Delta I_1}{\Delta t} \right| } \] Thus, the mutual inductance can be defined as the ratio between the emf generated in coil 2 and the rate of current change in coil 1. It is also known as the coefficient of mutual induction. Now, consider the following equation again. \[ N_2 \frac{\Delta \phi_{21}}{\Delta t} = M_{21} \frac{\Delta I_1}{\Delta t} \] The above equation is discrete in time. So, summing over all time increments we get \[ N_2 \Sigma \Big ( \frac{\Delta \phi_{21} }{\Delta t}\Big ) \Delta t = M_{21} \Sigma \Big ( \frac{\Delta I_1}{\Delta t} \Big ) \Delta t \\ \Rightarrow N_2 \phi_{21} = M_{21} I_1 \\ \Rightarrow M_{21} = \frac{N_2 \phi_{21}}{I_1} \] This equation is used to calculate the mutual inductance between any two coils, as discussed below. Suppose two coils 1 & 2 with N1 and N2 turn have currents I1 and I2 flowing through them, as shown in the figure. The flux due to I1 and I2 are φ21 and φ12. The mutual inductance of coil 2 due to coil 1 is given by \[ M_{21} = \frac{N_2 \phi_{21}}{I_1} \] Similarly, the mutual inductance of coil 1 due to coil 2 is given by \[ M_{12} = \frac{N_1 \phi_{12}}{I_2} \] From the reciprocity theorem, the two mutual inductances are the same and can be represented by M. Therefore, \[ M = M_{21} = M_{12} \\ \Rightarrow M = \frac{N_2 \phi_{21}}{I_1} = \frac{N_1 \phi_{12}}{I_2} \] The induced emfs in the two coils are given by \[ \epsilon_{21} = -M\frac{\Delta I_1}{\Delta t} \hspace{5mm} \text{and} \hspace{5mm} \epsilon_{12} = -M\frac{\Delta I_2}{\Delta t} \] Note that ε21 and ε12 do not represent the total emf in the circuit. Each coil can have its emf due to self-inductance. The mutual inductance depends upon how close the two coils are placed. If the coils are close enough, all the flux from coil 1 passes through coil 2. Then the mutual inductance is high. The mutual inductance is low if the coils are far. Also, the mutual inductance can be increased by increasing the number of turns of the coils or by enclosing the coils in a soft iron core. The advantage of having a soft iron core is that the magnetic flux leakage is reduced. Mutual Inductance Formula Between Two Coils Suppose a long solenoid with length d and cross-sectional area A consists of N1 turns of wire carries current I1, as shown in the figure. The magnetic field B inside a solenoid is given by \[ B = \frac{ \mu_o N_1 I_1}{d} \] Where μo (= 1.26 x 10-6 H/m) is called the permeability of air. A coil of N2 turns is wrapped around the solenoid such that the two are coaxial. The magnetic flux φ21 passing through each turn of the coil due to the solenoid is \[ \phi_{21} = BA = \frac{\mu_o N_1 I_1 A}{d} \] Thus, the mutual inductance is \[ M = \frac{N_2 \phi_{21}}{I_1} \\ \Rightarrow M = \frac{\mu_o N_1N_2 A}{d} \] The self-inductance of a solenoid is \[ L_1 = \frac{\mu_o N_1^2 A}{d} \] Similarly, the self-inductance of the coil can be calculated and shown to be \[ L_2 = \frac{\mu_o N_2^2 A}{d} \] Multiplying L1 with L2, we get \[ L_1 L_2 = \Big ( \frac{\mu_o N_1^2 A}{d} \Big ) \Big ( \frac{\mu_o N_2^2 A}{d} \Big ) = \Big ( \frac{\mu_o N_1N_2 A}{d} \Big )^2 = M^2 \\[10 pt] \Rightarrow M = \sqrt{L_1L_2} \] However, this equation assumes no flux leakage and perfect magnetic coupling between the two coils, L1 and L2. In reality, there is going to be some leakage due to alignment and the coupling can never be 100%. For this reason, we introduce a term calling coupling constant, k, such that the mutual inductance becomes \[ M = k \sqrt{L_1L_2} \] k takes a value between 0 and 1. When k = 1, it means that all of the magnetic flux produced by the solenoid passes through the outer coil and vice versa. Mutual Inductance of a Coil Wrapped Around a Solenoid Mutual inductance is widely used in daily life, especially in the following devices. TransformersGeneratorsMotorsMetal detectorsPacemakersRadio receivers Problem 1: Two coils have a mutual inductance of 4.75 × 10-4 H. The current in the first coil increases at a uniform rate of 940 A/s. What is the magnitude of induced emf in the second coil? Solution: Given M = 4.75 × 10-4 H ΔI/Δt = 940 A/s The induced emf is given by |ε| = M ΔI/Δt = 4.75 × 10-4 H x 940 A/s = 0.45 V Problem 2: Calculate the mutual inductance between a solenoid of length 30 cm and cross-sectional area of 6.25 cm2 with 500 turns and a circular coil of 250 turns wound at the solenoid's center (μo = 1.26 x 10-6 H/m). Solution: Given d = 30 cm = 0.3 m A = 6.25 cm2 = 6.25 x 10-4 m2 N1 = 500 N2 = 250 μo = 1.26 x 10-6 H/m The mutual inductance is given by M = μoN1N2A/d Or, M = 1.26 x 10-6 H/m x 500 x 250 x 6.25 x 10-4 m2/0.3 m Or, M = 0.000328 H or 3.28 x 10-4 H Q.1. Can mutual inductance be negative? Ans. The mutual inductance can be negative depending upon the orientation of the two coils and the current direction in each one. Article was last reviewed on Friday, February 3, 2023 Definition: Mutual Inductance between the two coils is defined as the property of the coil due to which it opposes the change of current in the other coil, or you can say in the neighbouring coil. When the current in the neighbouring coil changes, the flux sets up in the coil and because of this, changing flux emf is induced in the coil called Mutually Induced emf and the phenomenon is known as Mutual Inductance. Let us understand the phenomenon of Mutual Inductance by considering an example as shown in the above figure. Two coils namely coil A and coil B are placed nearer to each other. When the switch S is closed, and the current flows in the coil, it sets up the flux φ in the coil A and emf is induced in the coil and if the value of the current is changed by varying the value of the resistance (R), the flux linking with the coil B also changes because of this changing current. Thus this phenomenon of the linking flux of the coil A with the other coil, B is called Mutual Inductance. For determining the Mutual Inductance between the two coils, the following expression is used This expression is used when the magnitude of mutually induced emf in the coil and the rate of change of current in the neighbouring coil is known. If em = 1 volt and dI1/dt = 1 ampere then putting this value in the equation (1) we get the value of mutual inductance as M=1 Henry Hence, from the above statement, you can define Mutual Inductance as "the two coils are said to have a mutual inductance of one Henry if an emf of 1 volt is induced in one coil or say primary coil when the current flowing through the other neighbouring coil or secondary coil is changing at the rate of 1 ampere/second". Mutual inductance can also be expressed in another way as shown below Equating equation (2) and (3) you will get The above expression is used when the flux linkage (N2φ12) of one coil due to the current (I1) flowing through the other coil are known. The value of Mutual Inductance (M) depends upon the following factors Number of turns in the secondary or neighboring coil Cross-sectional area Closeness of the two coils Mutual Coupling In the Magnetic Circuit When on a magnetic core, two or more than two coils are wound, the coils are said to be mutually coupled. The current, when passed in any of the coils wound around the magnetic core, produces flux which links all the coils together and also the one in which current is passed. Hence, there will be both self-induced emf and mutual induced emf in each of the coils. The best example of the mutual inductance is the transformer, which works on the principle of Faraday's Law of Electromagnetic Induction. Faraday's law of electromagnetic induction states that " the magnitude of voltage is directly proportional to the rate of change of flux." which is explained in the topic Faraday's Law of Electromagnetic Induction. Mutual inductance is a fundamental concept in the field of electromagnetism, describing the relationship between two circuits that are placed in close proximity to one another. Specifically, it refers to the degree to which a change in the magnetic field of one circuit induces a voltage in another circuit, and vice versa. This phenomenon is governed by Faraday's law of electromagnetic induction, which states that a changing magnetic field will induce an electromotive force (EMF) in any conductor that is within the field. The strength of mutual inductance is determined by a number of factors, including the geometry of the two circuits, the distance between them, the magnetic permeability of the materials involved, and the number of turns in the coils. When two circuits are close together and have a high degree of mutual inductance, a change in the current in one circuit will cause a corresponding change in the current in the other circuit, leading to a complex and dynamic interaction between the two systems. Understanding Induced Voltage One of the key consequences of mutual inductance is the induction of voltage in a circuit when it is placed near a changing magnetic field. This voltage is known as an induced voltage, and it is proportional to the rate of change of the magnetic field. The induced voltage can be calculated using Faraday's law, which states that the induced EMF is equal to the negative rate of change of the magnetic flux through the circuit. The induced voltage can be either positive or negative, depending on the direction of the change in the magnetic field and the orientation of the circuit relative to the field. This induced voltage can be used for a range of purposes, such as generating electrical power in a generator, detecting changes in the magnetic field in a sensor, or transmitting data in a magnetic communication system. Mutual Inductance Examples There are many examples of mutual inductance in everyday life, such as in transformers, motors, and generators. In a transformer, two coils of wire are wound around a common magnetic core, and AC voltage is applied to one of the coils. This creates a changing magnetic field, which induces an AC voltage in the second coil. This voltage can then be used to power a load or to step up or step down the voltage for transmission over long distances. In a motor, the interaction between the rotor and stator windings creates a changing magnetic field that induces a voltage in the rotor, causing it to rotate. Similarly, in a generator, the rotation of the rotor within a magnetic field induces a voltage in the stator windings, generating electrical power. Applications of Mutual Inductance Mutual inductance has a wide range of applications in modern technology, from power generation and transmission to wireless communication and sensing. In wireless power transfer systems, for example, mutual inductance is used to transfer power wirelessly between a transmitter coil and a receiver coil, eliminating the need for physical connections. In magnetic sensors, mutual inductance is used to detect changes in the magnetic field, enabling the measurement of parameters such as position, distance, and direction. Similarly, in magnetic communication systems, mutual inductance is used to transmit data wirelessly between two devices, providing a secure and efficient means of communication in environments where other wireless technologies may be unreliable. Overall, mutual inductance is a fundamental concept that plays a crucial role in many areas of modern technology, enabling the efficient transfer of energy and information between different systems. The topic of induction was first given by Oersted by discovering that a magnetic field is produced through an electric field. After this, different scientists started to think can the reverse is possible .i.e. can we produce electric current from a magnetic field. Michael Faraday and Joseph Henry simultaneously established that an electric current is generated in a coil when the coil and a magnet are in relative motion. The current produced here is called induced current and e.m.f produced are called induced e.m.f. In this topic, we will see what is Electromagnetic Induction and one of its types which is Mutual induction. Electromagnetic Induction Electromagnetic induction is the phenomenon of changing magnetic flux or field causing an induced e.m.f. in a conductor or conducting coil. The idea of magnetic flux or field, which may be represented by magnetic field lines, is important to understand while researching electromagnetic induction. The direction of magnetic induction at any given place is determined by the tangent to the magnetic field lines. There are two types of Electromagnetic Induction they are, Self InductionMutual InductionMutual Induction When two coils are kept near each other and current change in one coil is causing e.m.f change in other then this phenomenon is called mutual induction. Consider the circuit given below, As shown in the above figure, let there be two coils placed close to each other namely P and S. The coil P has a power source (E) and a key (k) and coil S has a galvanometer to detect the deflection. Here, let coil P be Primary coil and coil S be Secondary coil. Working: The galvanometer indicates momentary deflection in one direction and deflection in the other direction when key 'K' is closed. When the galvanometer shows that the current flowing through primary (P) is constant or zero when the key is turned open, no deflection is created in the galvanometer. However, when the current flowing through the main coil changes, a phenomenon is known as "Mutual Induction" occurs, and the secondary coil's e.m.f. is induced. We can see the induced e.m.f by checking the deflection in the galvanometer. Magnetic Flux (φ): The number of magnetic field lines passing through a closed surface is known as magnetic flux. It calculates the total magnetic field that travels across a specific surface area. Explanation: The magnetic flux w.r.t coil S at any instance is related to the current flowing through the primary coil at that instance. φs α ip ∴ φs = M×ip Here, M is the coefficient of mutual inductance of the coil So, we can find e.m.f. induced in the secondary coil (S) at any instant, es = - dφs / dt es = -d(M×ip)/dt es = -M dip /dt |es| = |-M dip/dt| |es| = M dip / dt| M = es / |dip / dt| Coefficient of mutual induction: The coefficient of mutual induction can be defined as the ratio of e.m.f. induced in one coil to the rate of change of current in the next coil. Mutual inductance depends on the number of turns on the coil, size of the coil, separation between each turn and the angle of the turns, and the medium where the coils are placed. S.I Unit of mutual inductance is Henry (H) Dimensions of mutual induction are [L2M1T-2I-2] Examples of Mutual inductance An electric clothes dryer's heating coils can be counter-wound such that their magnetic fields cancel out, considerably lowering mutual inductance with the dryer's housing.The essential functioning principle of transformers, motors, generators, etc.All the electric components deal with a magnetic field. Significance of Mutual Induction As discussed in previous examples the mutual induction is essential to all the electric equipment that uses a magnetic field so it is very significant in the modern world.Electric motors also use their principal and are a very important piece of equipment.A transformer's mutual inductance, also known as the coefficient of coupling, is a measurement of the efficiency with which power is transmitted from the primary to secondary coils.When two coils are placed close together, the magnetic field in one of them tends to connect with the magnetic field in the other. The second coil then generates a voltage as a result of this. Mutual inductance is the property of a coil that influences or modifies the current and voltage in a secondary coil.When two coils are placed close together, the magnetic field in one of them tends to connect with the magnetic field in the other. The second coil then generates a voltage as a result of this.Eddy current and its relation to mutual induction According to Faraday's law of induction, eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor. Within conductors, eddy currents flow in closed loops in planes perpendicular to the magnetic field. Example of eddy current, speedometer in our vehicle. Mutual induction is the principal cause of eddy current formation and generation in the test material. An alternating current is transmitted through a wire coil as the test material. An eddy cope device is then attached to the probe. Any conductive substance can be used for the next circuit. A magnetic field is generated in and around a coil when electricity is conducted through it. When a probe is introduced close to a conducting substance, the alternating magnetic field of the probe causes current to flow through it. These currents run in closed loops at right angles to the magnetic flux in a plane. Eddy currents are what we call them. These eddy currents generate their magnetic field, which interacts with the coil's primary magnetic field. Analyzing the variances in the resistance and inductive reactance of the provided coil might provide information about the test material. Coupling Coefficient: It's the open circuit to actual voltage ratio, as well as the ratio obtained if the flux is connected from one circuit to the other. It is related to mutual inductance and is a simple approach to comprehend the relationship between certain inductor orientations and arbitrary inductance. Sample Questions Question 1: Why is this inductance called "mutual Induction"? Answer: This induction is produced by two the induction produced on each other by two adjacent circuits thus it is the current produced Mutually between two circuits thus it is named mutual induction. Question 2: What is the induced e.m.f. in a circular coil kept in a magnetic field? Answer: There is no variation in magnetic flux created since the coil is in a homogeneous magnetic field. As a result, the coil has no induced e.m.f. Question 3: What are the S.I Unit and Dimensions of Mutual Induction? Answer: S.I Unit of mutual inductance is Henry (H) and Dimensions of mutual induction are [L2M1T-2I-2] Question 4: What factors have an impact on mutual inductance? Answer: The factors that effects the mutual inductance are: Cross-sectional areaNumber of turnsthe amount of space between the two coils.Medium permeability between the two coilsDimensions Question 5: What is magnetic flux? Answer: Magnetic Flux (φ): Magnetic flux is the number of magnetic field lines traveling through a closed surface. It determines the overall magnetic field that goes across a certain region. Question 6: Where do we use the principle of mutual induction? Answer: We mostly use mutual induction in, transformers, generators, and all the electronic devices which use a magnetic field. Question 7: Two coaxial coils are very closer to each other and their mutual inductance is 10mH. If a current (60 A) sin 600t is passed in one of the coils, then find the peak value of induced e.m.f. in the secondary coil. Answer: i = 60 sin 600t e.m.f. here can be given by, e = -M di/dt e = -(10 × 103) d (60 sin 600t)/dt e = -10 × 103 × 60 cos 600t ×600 e = -360 cos 600t Thus according to the Mutual induction formula e = M×ip Induced e.m.f. in secondary coil is 360V The e.m.f. is induced in a circuit if it links with the changing flux produced by the other neighbouring coil. This e.m.f. is known as mutually induced e.m.f. and the phenomenon is known as mutual induction. Fig. 1. Mutual induction. The figure shows two coils A and B placed side by side. A galvanometer is connected across the coil B and coil A is connected to a battery through an ammeter and variable resistance to vary the current. When the switch is on, the current changes producing a changing magnetic field which links the coil B and according to the Faradays laws of electromagnetic induction the e.m.f. is induced in coil B. The induction of voltage will last only as long as the change of flux is there. This e.m.f. is known as mutually induced e.m.f. and the phenomenon of induction as the mutual induction. Uses. This principle is used in two winding transformers on a.c. where the direction and magnitude of the current always keeps on changing. Coefficient of mutual induction (M) It is denoted by the letter M. If there are two coils having N1 and N2 number of turns; than the coefficient of mutual inductance between the two coils is defined as the weber-turns in one coil due to one ampere current in the other neighbouring coil. Let there be I, ampere current flowing in one coil produces Φ1 Wb. flux. Now this flux links with the second coil without loss of any flux. Now the flux linkage (Weber turns) in the second coil for unit current in the first coil are \[=\frac{{{N}_{2}}\cdot {{\phi }_{1}}}{{{I}_{1}}}\] Now by definition, we can say that \[M=\frac{{{N}_{2}}{{\phi }_{1}}}{{{I}_{1}}}\] if N1Φ1 = 1 and I = 1 A in that case M = l, which can be defined as the two coils are said to have a mutual inductance of 1 H if one ampere current when flowing in one coil produces a flux linkage of one Wb-turn in the other neighbouring coil. It can otherwise be defined as two coils will have a mutual inductance of one henry if a current changing at the rate of one ampere per second in one coil induces an e.m.f. of one volt in the other coil. Coefficient of coupling L1 = Coefficient of self inductance of coil 1 L2 = Coefficient of self inductance of second coil. M = Coefficient of mutual inductance, Then \[M=K\sqrt{{{L}_{1}}{{L}_{2}}}\] or \[K=\frac{M}{\sqrt{{{L}_{1}}{{L}_{2}}}}\] When the two coils are tightly coupled i.e. the flux produced by coil links with the other coil completely the K, coupling coefficient is unity. If the flux produced by one coil does not link the other coil than the value of coefficient of coupling is zero i.e. the coils are magnetically isolated from each other.