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EFFECTS OF HARMONICS ON POWER & COMMUNICATION SYSTEMS

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By

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General:

If Sinusoidal waveform is applied to a device which has non-linear current / voltage relationship, the resulting current will not be sinusoidal in waveform. This distorted waveform will be made up of sum of components whose frequencies are harmonically related to that of fundamental. Non-sinusoidal waves are complex wave, **instantaneous value** of which is given by:

$i = I_0 + I_{1m} \text{ Sin } (wt + f_1) + I_{2m} \text{ Sin } (2wt + f_2) + I_{3m} \text{ Sin } (3wt + f_3) + \ldots\ldots\ldots\ldots\ldots$ (i)

where,

I_0 = D.C Component

i_{1m}, I_{2m} ……. are peak values of currents

ϕ_1, ϕ_2……..are phases of relevant harmonics.

R.M.S current, I is given by:

$I = \sqrt{(\text{average value of } i^2)}$

Now,

$i^2 = I_0^2 + I_{1m}^2 \text{ Sin}^2 (\omega t + \phi_1) + I_{2m}^2 \text{ Sin}^2 (2\omega t + \phi_2) + I_{3m}^2 \text{ Sin}^2 (3\omega t + \phi_3) + \ldots\ldots + 2I_{1m.} I_{2m} \text{ Sin}(wt + f_1).\text{Sin}(2wt + f_2)\ldots\ldots + 2I_{0.} I_{1m} \text{ Sin}(wt + f_1) + \ldots\ldots\ldots\ldots$

The above term consists of three products

(a) Self product of term of same frequency.

(b) Cross products of two terms of differing frequencies.

(c) Product of D.C component with each harmonic.

- The average value of self product over one cycle is given by:

$$\frac{1}{2\pi}. \int_0^{2\pi} Inm^2 . \text{Sin}^2 (n\omega t + \varphi n). d(\omega t)$$

Which readily simplifies to $\frac{Inm^2}{2}$

- The average value of I_0^2 is I_0^2

- The average value of cross products are zero, since

$$\int_0^{2\pi} \mathrm{Sin}(\ p\omega t + \varphi p).\ \mathrm{Sin}(\ q\omega t + \varphi q)\, d(\omega t) \ = 0$$

- Products of D.C component with each harmonic are zero, since

$$\int_0^{2\pi} \mathrm{Sin}(\ p\omega t + \varphi p).\ d(\omega t) \ = 0$$

Average value of $i^2 = \left(I_0^2 + \frac{I_{1m}^2}{2} + \frac{I_{2m}^2}{2} + \ldots.\right)$

RMS value of current is given as:

$I = \sqrt{\left(I_0^2 + \frac{I_{1m}^2}{2} + \frac{I_{2m}^2}{2} + \ldots.\right)}$ **[1]**

Equation (i) can be written in the following form:

$Y = f(x) = a_0 + a_1.\mathrm{Sin}(x) + a_2.\mathrm{Sin}(2x) + a_3.\mathrm{Sin}(3x) + \ldots. + b_1.\cos(x) + b_2.\cos(2x) + b_3.(\cos 3x) + \ldots\ldots\ldots\ldots$(ii)

This is a form of Fourier series and its Coefficients are:

$$\mathbf{a_0} = \frac{1}{2\pi} \int_0^{2\pi} f(x).dx$$

$$\mathbf{a_n} = \frac{1}{2\pi}. \int_0^{2\pi} f(x).\mathrm{Sin}\ x.dx$$

$$\mathbf{b_n} = \frac{1}{2\pi}. \int_0^{2\pi} f(x).\mathrm{Cos}\ x.dx$$

$\mathbf{a_0}$ is called D.C component and will be zero if areas of positive and negative half cycles over a period are equal.

If $f(x + \pi) = - f(x)$, negative half cycle will be reflection of positive half cycle and there will be no even harmonics.

If $f(-x) = f(x)$, $\mathbf{a_n} = 0$ and there are no sine terms.

If $f(-x) = - f(x)$, $\mathbf{b_n} = 0$ and there are no cosine terms . **[3]**

Iron core coils, Rectifiers, Transformers, Power amplifiers are some of the devices having non-linear current voltage relation, thus producing harmonics.

Due to harmonics the waveform is distorted and distortion depends upon Type and order of harmonics, their percentage contents, phase displacement relative to fundamental etc. Wave shape requirements of synchronous machines are defined by all American, British and IEC specifications.

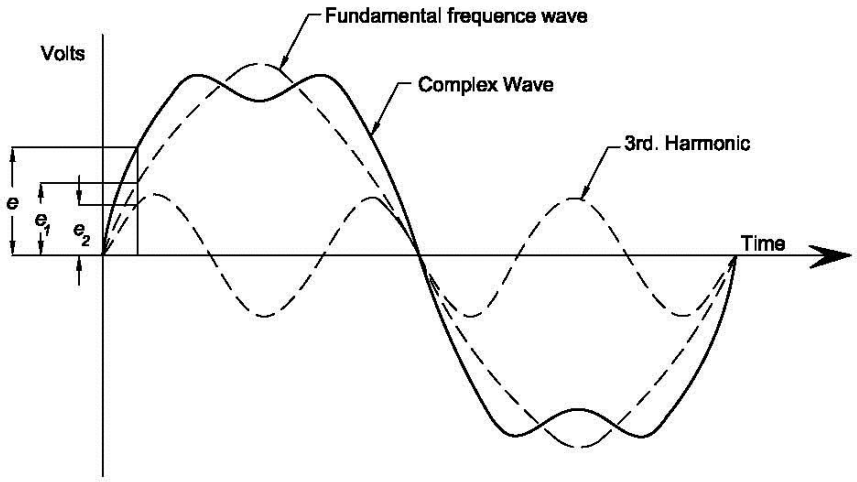


Fig. 1 : Wave-form with a 3rd harmonic in phase relative to fundamental

Fig. 1 shows distortion of fundamental sine wave in the presence of 3rd harmonic, when the fundamental and harmonic start from zero together and their phase differences with respect to the complex wave are zero. The resulting complex wave is flat topped.

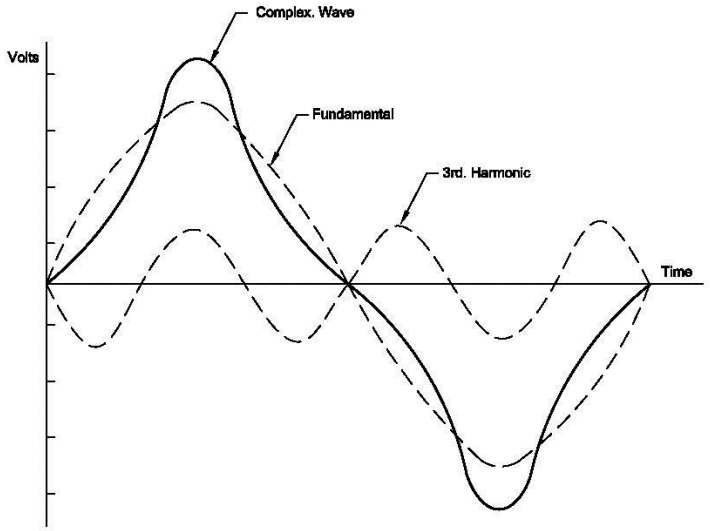


Fig. 2 : Wave form with a 3rd harmonic displaced 180° relative to fundamental

Fig. 2 shows waveform in the presence of third harmonic which is displaced in phase by 180° relative to fundamental. The waveform is peaked instead of flat top.

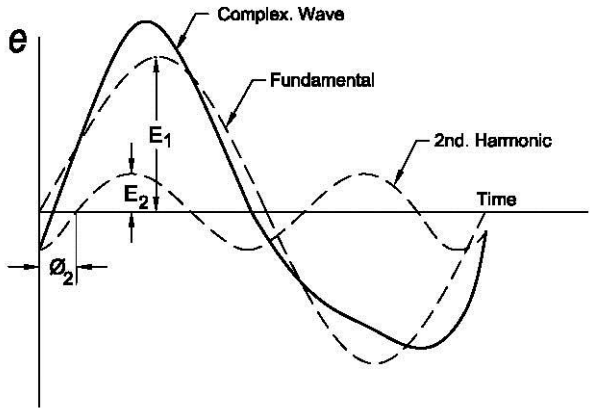


Fig. 3 : Wave-form Containing Second Harmonic

In the presence of even harmonics the shape of negative half wave will become different from that of positive half wave. Fig. 3 shows waveform containing 2nd harmonic due to which the negative half wave shape has deformed. **[2]**

Sources of harmonics:

Important source of harmonics in most power systems are synchronous generators, motors, frequency converters, rectifiers , transformers etc.

Harmonic due to Synchronous machines.

In synchronous machines harmonics are generated from slot frequencies and their values are given by :

$\mathbf{F_s}$ = Q (RPS) ± F

=Q. $\left(F * \frac{2}{p}\right)$ ±F

= (2. Q_p ±1). F

Where,

Q is total number of armature slots

RPS is machine speed in Revolutions per second.

F is fundamental frequency.

Q_p is number of slots per pole.

P is No. of poles

Frequency given by the above term corresponds to pulsation of reluctance in the magnetic circuit. Because of the effect of rotation of the rotor the harmonics appearing in the armature circuits are increased and decreased by the fundamental. Thus if slot frequency corresponds to 18th harmonic, the frequency appearing in the output circuit will be 17th and 19th harmonic of fundamental. The slot frequency always appear in pairs but their magnitudes are always quite different. Double frequency pulsation are produced by saturation of magnetic circuit (especially in teeth) and by reflection from currents in rotor bar by slot ripples.

Harmonics in synchronous machines can be controlled by keeping suitable ratio of slot opening to air gaps, shaping of pole pieces, avoidance of certain number of slots per pole per phase, skewing of poles or slots, applying chorded or fractional slot windings. **[6]**

Harmonics due to Induction motors.

The most important harmonics produced by Induction motors are caused by reluctance changes introduced by stator and rotor slots and their harmonic frequencies are:

$\mathbf{F_s}$ = Qs (RPS) ± F

$\mathbf{F_r}$ = Qr (RPS) ± F

Where;

$\mathbf{Q_s}$ and $\mathbf{Q_r}$ are rotor and stator slots

$\mathbf{F_s}$ and $\mathbf{F_r}$ are stator and rotor frequencies

RPS is speed of rotor in revolutions per second.

F is system frequency. 50 HZ or 60 HZ

Slot harmonics occur in pair for both stator and rotor slots. Frequencies are related to actual speed of rotor and vary with slip. Certain slot numbers are not desirable especially one that would cause one of the harmonics from stator slots to be the same as one caused by rotor slots.

Additionally 2nd harmonics are also introduced by saturation of steel, mainly in the teeth. **[6]**

Harmonics due to transformers.

In transformers and reactors, harmonics are produced due to core saturation. According to law of magnetic circuits,

$\phi_i = i_{o\mu} . T / R_\mu$

where

ϕ_i = Magnetic flux

$i_{o\mu}$ = Magnetizing current

T_1 = Primary turns

R_μ = Reluctance of steel core.

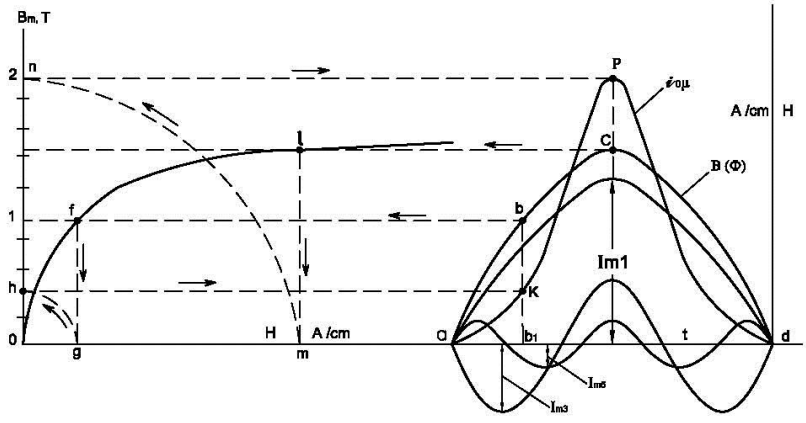


Fig. 4 : Plotting of curve $i_{0\mu} = f(t)$ and its resolution into first and higher harmonics

In power transformers core saturation is usual and when it happens, magnetizing current of a transformer will be non-sinusoidal, containing harmonics. The shape of current $i_{o\mu}$ curve and magnitude depends upon degree of steel saturation. Transformer sheet steel is not

saturated up to a flux of 0.8T. For this zone it can be assumed that magnetization current is proportional to flux density. Above 0.8 T up to 1.3 T flux densities correspond to bend of magnetization curve, i.e. medium saturated steel. Above 1.3 T flux densities correspond to various high degrees of steel saturation. Fig.4 shows magnetizing current curve $i_{o\mu}$ =f(t) plotted according to mean magnetization curve.

As is clear from above, no load current of a saturated steel will be non sinusoidal as can be seen from Fig.5 (curve 4). Magnetizing current $i_{o\mu}$ can be resolved into series of harmonics. Since the curve is symmetrical about the axis of abscissa there will be only odd harmonics, out of which the most pronounced are 3rd harmonics.

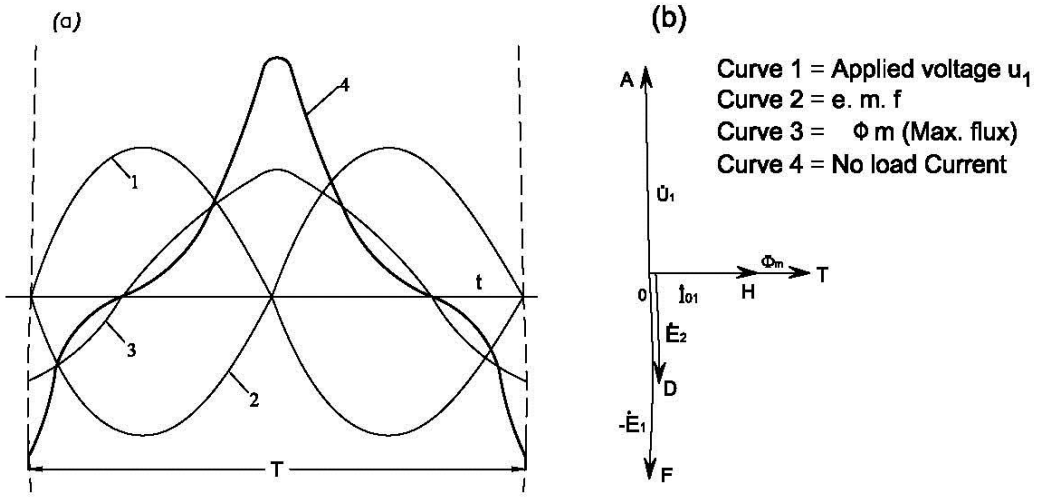


Fig. 5 : E. m. f. and current diagram for elementary single-phase transformer with saturated steel.
a - in rectangular co-ordinates; b - in vector form.

Saturation of steel and hence the sub harmonics cannot be totally avoided but with use of good sheet steel magnetizing, curve can be improved, so that saturation takes place at higher flux densities. **[4]**

Capacitors effects.

Unlike rotating machines, transformers or reactors, capacitors are not themselves source of harmonics. If harmonics exist in a circuit, change of impedance due to addition of capacitor increase or decrease harmonic currents. In capacitors principal cause of harmonic currents is magnetization requirement of system transformers. Because of lower impedance of capacitor at higher frequencies, the harmonic currents may become high enough to endanger the life of capacitor. For this purpose, margin is kept in the capacitors to cater for harmonic voltages. If transformers are operated near the rated voltage, the harmonic voltages are limited to minimum values. Normally 3rd and 5th frequency harmonics are encountered in capacitors. According to International specifications capacitors are built so that combined harmonic and fundamental frequency Kvars do not exceed 135% of name plate rating. Since capacitors have lower reactance to higher frequencies, breakers applied with shunt capacitors must have sufficient current capacity to handle harmonic currents along with fundamental frequency currents.

When capacitors are used for power factor improvement, it is good practice to make calculations for required power factor and use partly in association with inductor for filtration of

most prominent harmonics. There will be increase in cost but it will be recovered in the long run due to reduction of losses and reduced possibility of damage to capacitors on account of high voltage.

Sources mentioned above are the most important sources of harmonics, which power engineers, come across daily. There are other numerous sources which effect power and communication systems. D.C Motor drives, welding loads, SCR bridges, inverters have impact on system frequency response. **[6]**

Adverse effects of harmonics:

At power frequency Harmonics are undesirable due to the following main reasons:

1. **Harmonics cause increased iron /hysteresis losses.**

   Wave form of a transformer magnetizing current contains proportion of harmonics which will increase as the peak flux density is raised to saturation condition. Transformer losses would increase accordingly.

   Eddy current loss is given by:

   $W_e = \frac{8.88^2 * f^2 * ß_{max}{}^2 * t^2 * 10^{-16}}{48\,\rho}$ watts per cm^3

   Similarly hysteresis loss is given by:

   $W_h = \eta \,.f.\, (B_{max.})^{1.6} \,.\, 10^{-7}$ watts per cm^3

Where;

f is frequency

B_{max} is maximum flux density in Weber/cm^2

't' is thickness of sheet in cm.

'η' is hysteresis constant of the steel sheet.

'ρ' is resistivity in ohms/cm^3

As can be seen eddy current losses are proportional to square of frequency. Thus if we consider third harmonics only, the losses will increase nine times that at fundamental frequency and hysteresis loss will be 3 times that at fundamental frequency**.** For higher harmonics losses would further increase. **[2]**

2. **Transformer Inrush current effects**

   Energization of power transformers will create 2nd harmonics due to inrush currents, causing distortion of waveform. Transformer protective devices need special 2nd harmonic filters apart from odd harmonics in the absence of which the relay will not differentiate between a fault and switching operation, thus causing indiscriminate tripping.

   When a transformer is energized the flux linking varies from a peak negative value to a peak positive value during half cycle of voltage wave. The flux change of twice the maximum value is proportional to time integral of voltage wave between successive zero points. On switching on at zero point of the voltage wave, with the flux initially zero, the maximum flux developed will be nearly twice the normal peak value as shown in fig. 6.(b). Increase of flux to double this value corresponds to extreme saturation. Magnetizing current will increase to a very high value, which may exceed the rated full load value. Residual flux can increase the current still further. If the initial remanant flux instead of being zero has initial positive value that is, initial value in the same direction as the flux change, the increment of flux must remain the same since it is proportional to half cycle voltage loop and the peak value attained will of the order of 2.8 times the normal value with 80 % remanence. These very high flux densities are far beyond the normal working range that the incremental relative permeability of the core approximates to unity and inductance of winding falls to a value nearly that of air cooled inductance. The current wave starting from zero increases slowly at first the flux having a value just

above the residual value and the permeability of core being moderately high. As the flux passes the normal working value and enters the high saturated portion of magnetizing characteristics the inductance falls and current rises rapidly to a peak which may be 500 times the steady state magnetizing current. When the peak is passed the next voltage zero, the following negative half cycle of the voltage wave reduces the flux to starting value, the current falling symmetrically to zero as shown in Fig. 6(c). The current wave is therefore completely offset. Switching at other instants of voltage wave will produce lower value of transient currents. **[8]**

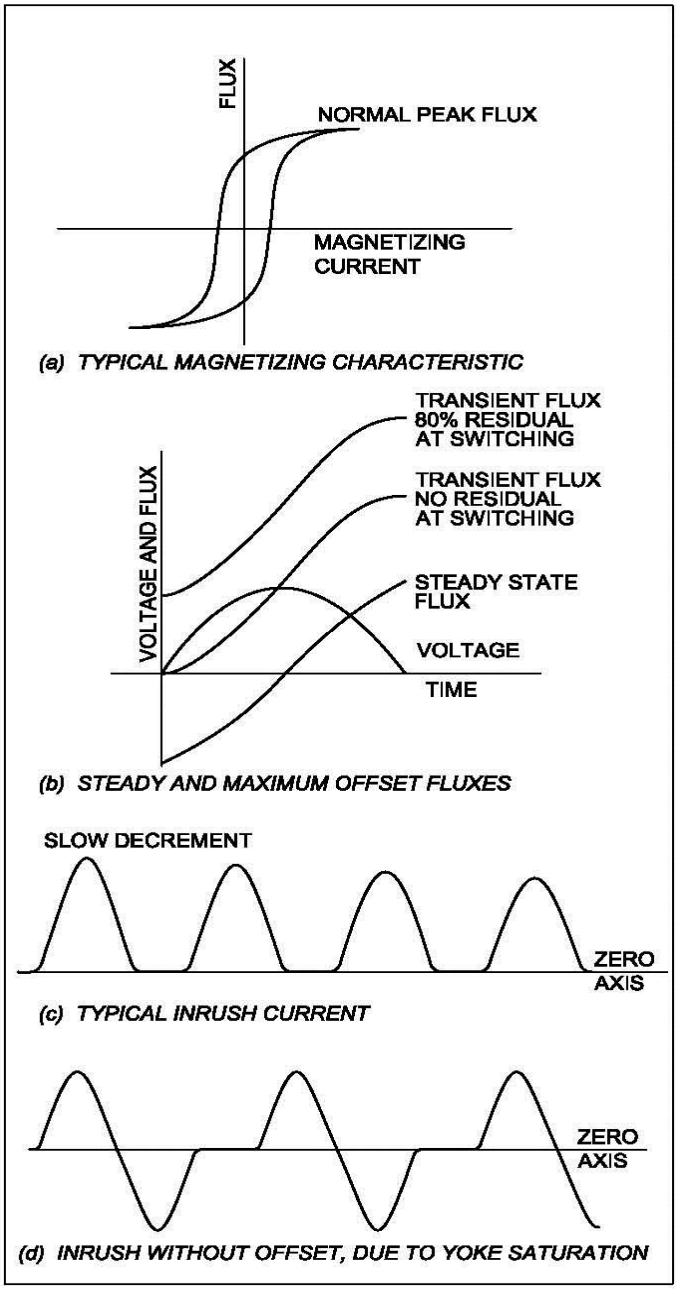


Fig. 6 : Transformer magnetizing inrush.

3. Circuit resonance

Circuit Resonance may occur at certain frequency, leading to extra-ordinary large harmonic currents.

If e.m.f of a complex wave form ; say

e= E1 sin (ωt+ϕ1) + E3 sin (3ωt+ϕ3) + E5 sin (5ωt+ϕ5) + ….

If this voltage is impressed upon a circuit containing resistance 'R', capacitance 'C' and inductance 'L' in series then

Current I= $\frac{E1.Sin(\omega t+\varphi 1-\Theta 1)}{\sqrt{\left(R^2+\left(\omega L-\frac{1}{\omega C}\right)^2\right)}}+\frac{E3.Sin(3\omega t+\varphi 3-\Theta 3)}{\sqrt{\left(R^2+\left(3\omega L-\frac{1}{3\omega C}\right)^2\right)}}+\frac{E5.Sin(5\omega t+\varphi 5-\Theta 5)}{\sqrt{\left(R^2+\left(5\omega L-\frac{1}{5\omega C}\right)^2\right)}}+\ldots\ldots\ldots$

Θ1, Θ3, Θ5….. are phase angles by which components of current wave lag behind e.m.f components producing them. Thus

$$tan\Theta 1=\frac{(\omega L-\frac{1}{\omega C})}{R}$$

$$tan\Theta 3=\frac{(3.\omega L-\frac{1}{3.\omega C})}{R}$$

$$tan\Theta 5=\frac{(5.\omega L-\frac{1}{5.\omega C})}{R}$$

If n. ωL = 1/nω.C, then resonance will occur at the n^{th} harmonic where 'n' is harmonic order. Net value of reactance in resonance will be zero and

$$I=\frac{e}{R}$$

Thus due to small value of resistance, current amplitude at that particular harmonic will be very high and will be in phase with e.m.f, producing it. **[2]**

In case of series resonance, e.m.f across inductance or capacitor will be very high (although e.m.f across capacitor and inductance together will be zero), jeopardizing the equipment. Voltage across capacitor, **C** will be higher than applied voltage if inductance, **L** is greater than $C.R^2$**.** Voltage across inductor **L** will be higher than applied voltage for all values of **L**.

4. Ferro-resonance

In a series resonant circuit, like a capacitive voltage transformer the excitation impedance of auxiliary transformer and capacitance of potential divider form a resonant circuit, oscillating at sub-harmonic frequency, ensuing during switching of supply voltage. Most probable frequency of oscillation is third harmonic frequency, although oscillation at other harmonic frequencies or at fundamental frequency is also possible. Principal manifestation of such oscillations is probable rise in the output voltage the r.m.s value being 25 % to 50 % above normal value. If the oscillation persists for several cycles it may be hazardous for the equipment connected to it.

The main differences between a linear resonant and ferro-resonant circuit are:

-- Possibility of vide range of parameter values.

-- Frequency of voltage and current wave may vary from sinusoidal wave.

-- Existence of steady state responses for a given configuration and parameters values.

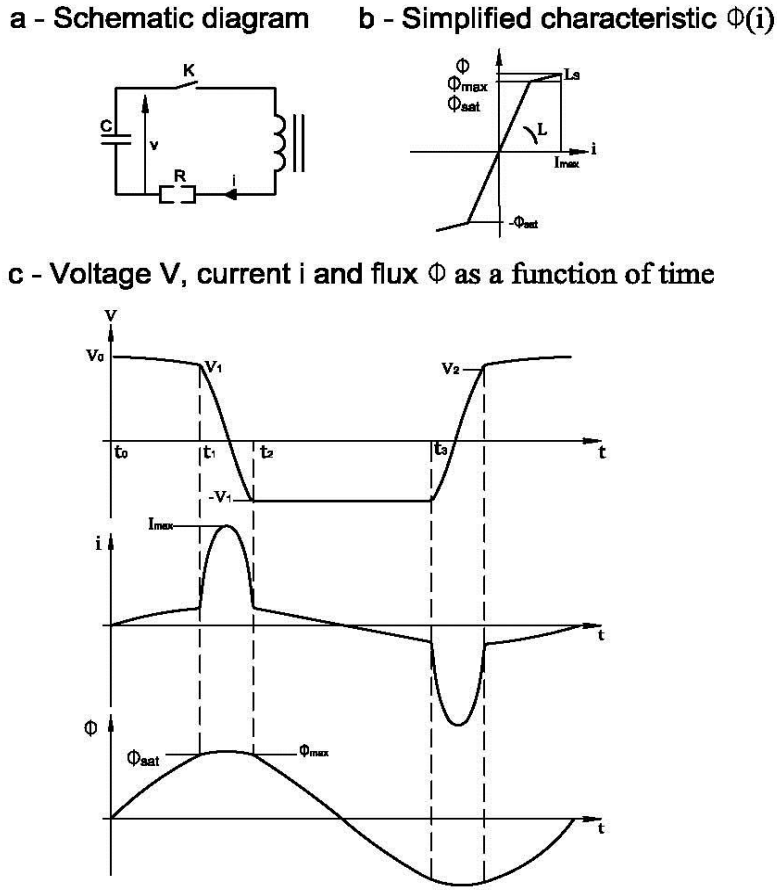


Fig. 7 : Free oscillations of a series ferroresonant circuit

The flux in the coil, $\phi = \frac{V0}{\omega 1}$. Sin $\omega_1 t$

Voltage across the capacitor terminal, v = V_0 . Cos $\omega_1 t$

If $\frac{V0}{\omega 1} > \phi_{sat,}$ at the end of time t_1, the flux ϕ_1 reaches saturation flux, ϕ_{sat} and voltage V = V_1 and inductance of the coil becomes L_s. L_s is small compared to L, the capacitor discharges across the coil in the form of an oscillation of pulsation, $\omega_2 = \left(\frac{1}{\sqrt{Ls.C}}\right)$

The current and flux reach peak when electromagnetic energy is equal to electrostatic energy $\frac{1}{2}.CV1^2$

At the instance t_2 the flux returns to ϕ_{sat} the inductance resumes the value L, voltage V1 reverses and becomes $-V_1$

At the instance t_3 the flux reaches $-\phi_{sat}$ and voltage V becomes $-V_2$

$\omega_1 = 1/\sqrt{(LC)}$

As ω_1 is in practice very small, we may consider

$V_2 = V_1 = V_0$

Time period, T is between $2.\pi\ \sqrt{(L.C)}$ (non-saturated case) and $2.\pi\ \sqrt{(L_s.C)} + 2.\ (t_3 - t_2)$ (saturated case) where,

$(t_3 - t_2) =$ $\frac{2}{V}$

The correspondence frequency, $f = \frac{1}{T}$ is such that

$1/(2.\pi.\sqrt{(LC)}) > f < 1/(2.\pi\ \sqrt{(L_s.C)})$

The initial frequency depends upon ϕ_{sat} and initial condition V_0. Due to i^2R loss, mainly at each voltage reversal, the amplitude of voltage, V decreases. $V_2 > V_1 < V_0$

Since the flux variation, $\Delta\phi$ during the non saturated period (t_3-t_2) is such that

$$\Delta\phi = 2.\ \varphi_{sat}\ .\ \int_{t2}^{t3} V dt$$

Thus decrease of V results in reduction of frequency. If energy losses are supplied by system voltage source, the frequency of oscillations, as it decreases can lock at the frequency of source; if the initial frequency is greater than power frequency or even at sub multiple of source frequency if initial frequency is smaller than power frequency.

Thus unlike linear resonance, at specific value of C, it can occur at wide range of C. This is main difference between linear resonance and ferro-resonance.

5. Impact on current transformer performance.

When a C.T is required to develop high secondary e.m.f under steady state condition, the non linearity of excitation system causes distortion of waveform and such a waveform in addition to fundamental contains odd harmonics. If C.T is saturated unidirectional, it will contain all orders of harmonics.

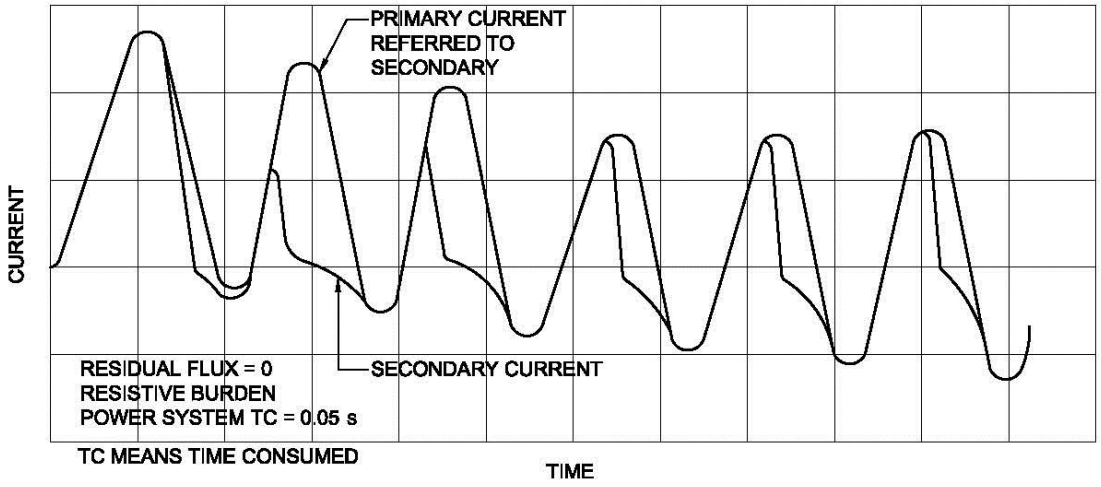


Fig. 8 : Distortion in secondary current due to saturation.

Lower order harmonics are of high amplitude and 2nd and 3rd order harmonics need special consideration. Due to saturation secondary output current will be distorted.

This is a matter of importance with certain protection systems which have special harmonic sensitivity.

Fig. 8 shows distorted secondary current due to saturation. Due to distortion, errors are introduced in C.T and response of protective relay towards is not as required.

6. Large third harmonic neutral current may exist in three phase system.

Harmonics of symmetrical 3-phase system are of definite sequence. Thus

Positive sequence harmonics are all of the order (6n + 1)

Negative sequence harmonics are all of the order (6n - 1)

Zero sequence harmonics are all of the order (6n - 3)

Where 'n' is an integer.

Sequence of odd harmonics is tabulated below:

Harmonic	Sequence	Harmonic	Sequence
1	Positive	7	Positive
3	Zero	9	Zero
5	Negative	11	Negative

In symmetrical system all the harmonics present in line to line voltage are contained in line to neutral voltages as well but third harmonic currents need special consideration, which in some cases are considerably large. Since third harmonics currents are of zero sequence, these will pass through the neutral of three phase system, even if the system is balanced. Like zero sequence currents triple harmonic currents are all in phase and of the same magnitude as illustrated by:

Ia_{3m} = I Sin 3mωt

Ib_{3m} =I.Sin[3m(ωt-2π/3)] = I.Sin 3mωt

Ic_{3m} =I.Sin[3m(ωt+2π/3)] = I.Sin 3mωt

Thus $I_{a(3m)} = Ib_{(3m)} = Ic_{(3m)}$

Thus total 3rd harmonic current flowing in neutral will be three times that in each phase.

7. Possibility of interference with communication system.

The switching of thyristors, triacs etc. gives rise to mains-borne harmonics in the radio frequency range. The radio frequency interference with communication systems can either originate from the devices themselves or from load equipment or via radiation from main supply lines. Screening of equipment will eliminate most of the directly radiated interference but not that from the mains for which filters must be used.

When power and telecommunication circuits are operating in proximity, power circuits may produce conductive or inductive effects, which interfere with normal operation of communication system. This effect is severe in the presence of certain harmonic frequencies which need to be identified for remedial action. Such harmonic frequency currents if in the audio or noise frequency range will interfere with telephone system. To investigate Noise frequency coordination problem between power and telephone systems, determination of harmonic voltages in the power system, coupling factor between power and communication circuits and harmonic current produced in telephone receivers are to be determined.

8. Some usual problems; like malfunctioning of computers, flickering of florescent lights, shut-down of electronic equipment, fuse blowing for apparently no reason and motors overheating etc. are encountered,

Conclusion:

As is visualized from the above discussions, harmonics of higher order as multiple of fundamental or sub-harmonics have adverse effect on the system. It may have one or more of the following effects:

i. Change of waveform, effecting the equipment performance.
ii. Result in high transformer losses.
iii. Result in transmission losses.
iv. Result in voltage rise, jeopardizing the equipment.
v. Result in failure of relay or spurious response of protective relay towards the fault.
vi. Produce errors in measuring instruments.
vii. Can interfere with communication system.

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