“ELECTRO-THERMAL DYNAMICS OF LV IRON CORE REACTORS AND THEIR IMPACT ON PERFORMANCE OF LV APFC SYSTEMS APPLIED IN NETWORKS AFFECTED BY HARMONICS”

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Abstract:
The continuing increase of variable loads, many of which are non-linear, in LV networks, combined with the targeting of high monthly average power factor calls for using LV APFC Systems with defined harmonic blocking or filtering characteristics. This is generally achieved by combining within such LV APFC systems, at each step level, iron core reactors in series with power capacitors, i.e. an LC series circuit.
This increases the losses of the LV APFC system by 2 to 4 times depending on the quality of the iron core reactor. The increased thermal load if not managed well results in accelerated electrical ageing of capacitors & other constituents of LV APFC systems.
Variation in "Inductance" of such reactors during operating conditions due to their inherent "Linearity" limits can permanently alter the blocking/filtering characteristics of the LC circuit, leading to dangerous failure mechanisms of LV APFC systems.
This paper deals with the electro-thermal behaviour of iron core reactors as a product as well as when such reactors are combined with capacitors & applied in networks affected by harmonics. It identifies changes needed in defining specifications & testing requirements of iron core reactors & LV APFC systems with such reactors, to enable improved performance.

1 Application aspects

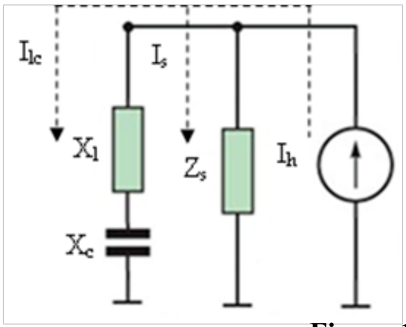
1.1 Harmonics

Non-linear loads, such as Variable speed drives, SMPS, UPSs, etc. draw non-sinusoidal current during each period of the sinusoidal supply voltage waveform. The interaction between such non-sinusoidal currents and impedances of the network result in distortion in the voltage waveform. Using Fourier series analysis, the distorted current and voltage waveforms can be decomposed into a series of sinusoidal waveforms having frequencies which are integral multiples of the fundamental frequency. These higher frequency components are called Harmonics. The presence of such harmonics causes a variety of negative effects in networks. In particular, when such networks involve the use of shunt capacitors for PFC additional problems can arise due to amplification of such harmonics, which in extreme cases could also involve resonance.

1.2 The LV APFC + Harmonics problem

Increasingly APFC systems with reactor + capacitor combinations at each step level are being used for the economic operation of electrical networks. The non-linear loads in such networks can be treated as current sources. The circuit analogy for this is shown in Figure 1. Mathematically, the harmonic current flow will be shared between the supply system and the LV APFC system. In order to avoid resonance, the ratio between X_l and

X_c is maintained as needed. For example, to avoid resonance risks for the 5th harmonic X_l=7% of X_{cy} is typically used.



I_h = Harmonic current generated by non-linear loads
I_s = Harmonic Current flowing in Supply network
I_{lc} = Harmonic Current flowing in APFC system
X_l = Inductive Reactance of the Reactor
X_c = Capacitive Reactance of the Capacitor
Z_s = Impedance of the supply network

Figure 1: Equivalent circuit

1.3 Specifying the Reactor

Iron core reactors are generally used in series with capacitors in LV APFC systems. They are of the dry type, Aluminium/Copper wound and are mounted inside the APFC panel. These reactors are required to comply with the relevant IS or IEC standards. In addition to specifying the rated kVAr, voltage and percentage tuning factor, the following parameters are critical to reactor performance and should be specified:

- Temperature class of insulation system and ambient temperature
- Linearity
- Harmonic voltage spectrum
- Losses

2 Factors Critical to reactor performance

2.1 Temperature class of insulation system and ambient temperature

The allowed temperature rise depends on insulation system. The maximum allowed ambient temperature defines starting point. The end temperature of insulation system defines maximum temperature and therefore the end point.

Example: A T40/H reactor (40°C ambient & Class H insulation) may be used in a 55⁰C ambient inside the APFC panel provided the temperature rise is controlled within limits.

- For the above reactor the permitted average temperature rise is 125°K
- Ambient 55⁰C => 55⁰C – 40⁰C = 15 K
- 125K – 15K = 110 K average temperature rise can be allowed above 55⁰C

2.2 Linearity

The reactor must maintain its "Inductance" within the permitted range at defined operating conditions. When saturation occurs, the inductance varies with changes in the current. This non-linear operation of the reactor will cause amplification of harmonics and in some cases, may lead to tuning of the LC filter to a harmonic frequency. Reactor currents would thus increase drastically and cause overloading of the reactor. For a given harmonic spectrum the minimum limit for the linearity current is the "arithmetic"sum of all harmonics plus fundamental current. For safety, a factor of 1.2 should be multiplied. This is based on the pratical experience of Hans Van Mangoldt (HVM) for over 45 years.

$$I_{LIN} = 1.2 \cdot \sum_h I_h$$

For this defined lineartity current, the reactor should not saturate. Reactors can be significantly cheaper if linearity limits are lower but this may lead to premature failure.

2.3 Harmonic voltage spectrum

The harmonic voltage spectrum & impedances at various harmonic frequencies will define each harmonic current in the reactor and thus its losses, ΔT and linearity behaviour. (Refer IEC 61642)

2.3.1 Calculation of harmonic currents

Formula to calculate the harmonic currents in the reactor (this is a derived formula)

$$i_h = \frac{(1-p)}{\left|\frac{1}{h} - h \cdot p\right|} \cdot u_h$$

Where, h is the harmonic order (h=3, 5, 7…)
i_h is the harmonic current of order h
p is the tuning factor(ratio of Xl to Xc)
u_h is the harmonic voltage of order h

UH3	UH5	UH7	UH11& UH13	THDU	IN=I1	I3	I5	I7	I11	I13	Irms	THD I
0.50%	2.60%	1.55%	0.00%	3.07%	131	4.95	21.15	5.45	0	0	133.12	17%
0.50%	4.00%	3.00%	0.00%	5.02%	131	4.95	32.54	10.55	0	0	135.70	26%
0.50%	5.00%	5.00%	0.00%	7.09%	131	4.95	40.68	17.58	0	0	138.59	34%
1.50%	7.00%	7.00%	0.50%	10.04%	131	14.84	56.95	24.61	0.9	7.19	146.08	49%
5.00%	8.00%	7.00%	4.00%	13.04%	131	49.47	65.08	24.61	0.73	5.86	156.66	65%

Table 1: Harmonic Currents for different voltage spectrums for a 440 V 50Hz 100 KVar 7% reactor

It can be seen that:

- For 3% THD (V), I_{rms} =133 A, with THD (I) being 17%.
- For 10% THD (V), I_{rms} = 146A, with THD (I) being 49%.
- Caution is needed in the selection and application of reactors, to minimise heat generated & to avoid saturation at operating levels.

2.4 Watt loss

The total losses W_t at I_{rms} > W_1at I_1 and are inter-related in a non linear mode.

- $\mathbf{W_1}$ is the loss at the fundamental current I_1, & is what is measured as per prevailing standards.
- $\mathbf{W_t}$ is the loss at I_{rms} (fundamental + all harmonics). Measurement of W_t is complex, as it needs a current injection system to generate all harmonics simultaneously.
- Increasing I_1 to I_{rms} will be of no relevance for this measurement as this current will basically heat up the winding while it will not heat up the core. Hence it cannot represent the real case with harmonic currents present

This is due to the nature of the loss mechanisms in the reactor:

- The I^2R losses or ohmic losses (including losses due to skin effect) are well understood phenomena.
- The core losses (W_{core}) however are mainly hysteresis and eddy current losses. They depend on the type of core material used & are proportional to

the frequency & the square of the frequency respectively. Therefore the core losses increase drastically in the presence of harmonics. The graphs shown in Fig 2 show the non-linear behaviour of these core losses.

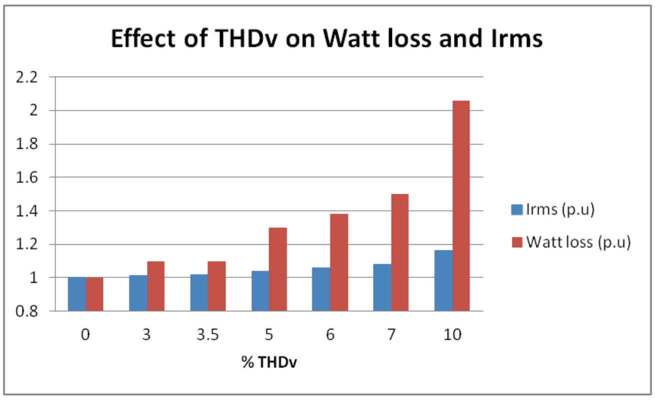


Figure 2: Effect of THDv on Reactor losses and Irms

3 Field Experiences

3.1 Voltage harmonic levels in the field

Table 2 shows the voltage THD at different voltage levels in an industry (where the incoming 110kV supply voltage is stepped down to 11kV and then further to 415 V).

Sl. No	System Voltage	Voltage THD %	Remarks
1	110 KV	0.4 %	THDv is lowest
2	11 KV	2.8 %	THDv is medium
3	415 V	6.8 %	THDv is highest

Table 2: Voltage THD at different voltage levels

From the utility point of view, the harmonics are usually measured at the point of coupling i.e. at the point of metering which is at HT side, where the harmonic voltage THD is lowest. Whereas the LV APFC panel is installed at the LV side where the harmonic voltage THD is highest & thus the detuned reactors will draw higher harmonic currents.

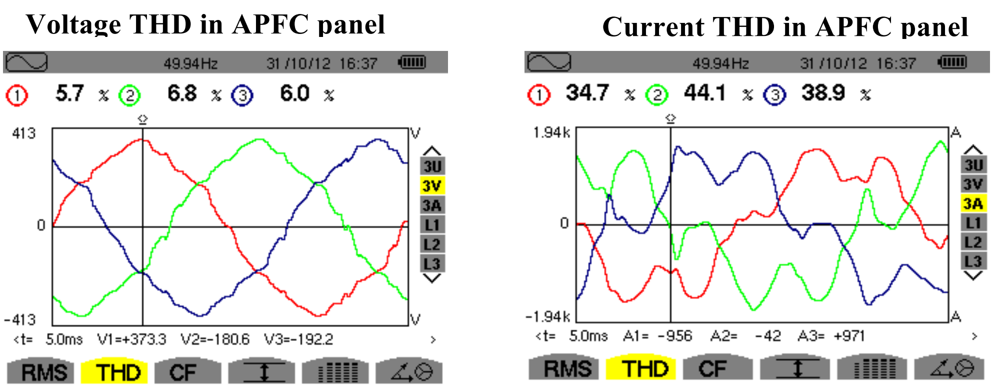
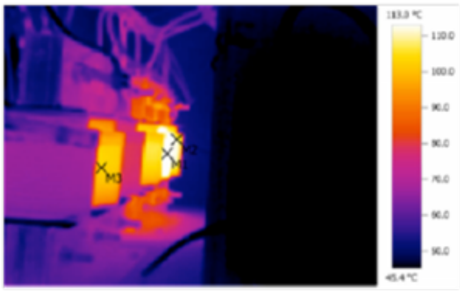


Figure 3: Snapshots of parameters for APFC panels with reactors

The voltage THD levels may range from 1% to 8% depending on the amount of non-linear loads present and also on the amount of harmonic injection from other nearby industries into the grid.

3.2 Thermal study of Reactors and other components of APFC panels

3.2.1 Thermal Study of a Reactor in an APFC Panel

<table>
<tr><th>Thermal image of reactors</th><th>Observations</th></tr>
<tr><td></td><td>
<table>
<tr><td>Measure point 1</td><td>122.3</td></tr>
<tr><td>Measure point 2</td><td>108.3</td></tr>
<tr><td>Measure point 3</td><td>102.5</td></tr>
</table>
- The hot spot on the reactor is 122.3 ^{0}C.
- The reactor makes a loud humming sound.
</td></tr>
</table>

3.2.2 Thermal Study of other components of APFC panels

<table>
<tr><th>Surface temperatures of other components</th><th>Observations</th></tr>
<tr><td>
<table>
<tr><th>Sl. No</th><th>Component</th><th>Surface temperature ^{0}C</th></tr>
<tr><td>1</td><td>ACB terminals</td><td>66.4</td></tr>
<tr><td>2</td><td>Contactors</td><td>53.1</td></tr>
<tr><td>3</td><td>Reactors</td><td>122</td></tr>
<tr><td>4</td><td>Thyristor switches</td><td>66</td></tr>
<tr><td>5</td><td>Capacitors</td><td>50</td></tr>
</table>
</td><td>
- The measured temperature of the reactor alone is 122 ^{0}C.
- The measured surface temperatures of all the components in the panel are less than 65 ^{0}C.
</td></tr>
</table>

4 Co-relating the theory & field experiences to highlight the negative influences of Reactor Losses & Linearity on Performance of LV APFC systems

Sl. no	Field Experiences	Theory	Remarks
1	Premature failure of reactors	Reactor operating beyond the Linearity limits	- Faulty reactor design - Sufficient air gaps not maintained, hence the reactor is operating in a saturated condition
2	Humming sound from the reactors	Reactor operating beyond the Linearity limits	- As the noise level in a reactor is proportional to the square of the flux density, a humming sound indicates a high core flux density - A loud humming sound may be an indication of the saturation of the core
3	High Reactor temperature	Reactor not sized to take care of the core losses	- Insufficient reactor core size
4	Reactor drawing more than rated current	Reactor is drawing excessive harmonic currents	- In the presence of a distorted supply voltage, the reactor draws harmonic currents - For 10% THDv, there is a 16% increase in Irms

5	Watt loss of reactor is high	Increase in winding & core losses due to excessive harmonic currents flowing into the reactor-capacitor unit	- For 10% THDv, there is a 106% increase in total losses(Wt) - The winding loss is represented by $(I_{rms})^2R$. - The core loss can be estimated by means of the flux density, frequency and by using material data sheet loss values.
6	Reduction in Life of capacitors in APFC panels	Increased micro ambient temperature inside the panel due to reactors	- Life of insulating material is halved for every 10 ^{0}C rise in temperature

5 Recommendation of changes to be made in Specification and Testing of LV Iron-Core Reactors

5.1 Compliance with Existing Standards

The detuned Iron-core reactors used in LV APFC systems should comply with the following standards: IS 5553 Part 5 and IEC 60076 Part 6.

5.2 Additional Specifications and Tests recommended

5.2.1 Mandatory Thermal Switch

- The provision of a thermal switch which can ensure disconnection of the reactor from the supply if its operating temperature exceeds the specified minimum limit should be made mandatory.
- Corresponding compliance standard for the Thermal Switch should be drafted.

5.2.2 Minimum linearity limit

- A minimum limit of linearity, at which the inductance remains with a tolerance of ±5% of its rated value (when measured according to a specified method) should be mandated in the standard along with a calculation procedure.
- Example: For a spectrum of UH1=100%, UH3=0.5%, UH5=UH7=5%, the linearity limits may be taken as shown in Table 3.

% Reactor	Linearity Current, I_{lin} (A)
5.67	≥2.14*In
7	≥1.8*In
14	≥1.42*In

Table 3: Linearity limits for different % Reactors

5.2.3 Noise level Test

- A noise level test may be mandated in the standard at specified test conditions with compliance limits.
- We suggest CPRI to evolve a test procedure accordingly.

5.3 Recommendations for future consideration

5.3.1 Utilization category of reactors for different voltage harmonic levels

- A Utilization category of the reactor may be defined based on the maximum Voltage THD% that the reactor can withstand. A suggested classification is shown in Table 4.

- End users or consultants may select the required category based on the site measurements of THDv or for the worst case conditions.

Utilization category	Max Voltage THD% withstand
A	3%
B	5%
C	7%
D	10%

Table 4: Utilization category based on different voltage harmonic levels

5.3.2 We suggest CPRI to evolve a procedure to measure the watt loss of such reactors in the presence of specified harmonics & evaluate if this may be introduced into the standards.

6 Conclusion

Iron Core Reactors are an indispensible part of LV APFC systems. The presence of harmonics has a detrimental effect on the temperature rise, linearity and Watt loss & thereby the performance. If these effects are not managed properly, it may lead to accelerated aging of the capacitors and premature failure of reactors & other components of the APFC system. The recommendations made above if incorporated will enable tighter standards which in turn can higher the level of performance by correct selection of reactors & tighter controls on testing and compliance.

7 References

[1] IEC 60076-6:2007, Power transformers – Part 6: Reactors

[2] IEC 61642:1997, Industrial a.c networks affected by harmonics – Application of filters and shunt capacitors

[3] IS 5553(Part 5):2004, Tuning Reactors