IMPORTANCE OF SUPPLY SHORT CIRCUIT CAPACITY AND IEEE 519 STANDARD FOR UTILITIES AND POWER CONSUMERS

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INTRODUCTION

Currently, most of the industries / consumers use non-linear loads receiving power supply at different voltages from the utilities. Both the utilities and consumers are concerned of the current harmonics generated by the non-linear loads injected into the supply networks. The governing standard for these harmonics (current as well as voltage) so far has been IEEE 519 (1992) [1] and now it should be the latest version published in 2014 [2].

It is necessary that both the utilities and consumers understand practical aspects of using the IEEE 519 standard, the relevance of short circuit capacity at the Point of Common Coupling (PCC), and technical issues involved thereof. This paper is intended to cover these aspects in detail and help both the utilities and the consumers work for a better power / distribution system.

UTILITY SCENARIO

As per requirements of utility (in existence for the last two years), the consumers need to adhere to total current harmonic injection below 3% and individual current harmonics below 1% at the PCC of the consumer's load. As learnt, this specification considers voltages below 69 kV as per recommendation based on IEEE 519 (1992) standard. However, in general the arguments or conclusions given here are also valid for voltages beyond 69 kV.

It is also true that when the above specifications came into existence two years back, IEEE 519 (1992) was applicable, while IEEE 519 (2014) standard came into existence recently. It is for this reason; the paper still gives more considerations for the presented analysis based on IEEE 519 (1992) standard than its recently published version in 2014. It should be noted that IEEE 519 (2014) standard now specifies 5% individual voltage distortion and 8% total harmonic voltage distortion, specifically for voltages ≤ 1 kV. By and large, hence, even though the discussion below is based on IEEE 519 (1992) standard, it can be considered same as if it is based on IEEE 519 (2014) standard.

It is understood that "Harmonic" means a component of a periodic wave having frequency that is an integral multiple of the fundamental power line frequency (50/60/$16^{2/3}$, more importantly 50 Hz in India) causing distortion to pure sinusoidal waveform of voltage or current. The relevant information on harmonic control (current and voltage distortion) is given in Annexure – A as per IEEE 519 (1992) standard.

It should be noted that IEEE 519 (1992 or 2014) standard is for "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems" and gives a guideline for harmonious working of power or distribution systems and the presently used non-linear loads controlled by power electronic converters generating various current / voltage harmonics.

Having understood utility requirements as specified two years back and considering the applicable reference standard IEEE 519 (1992), few technical issues come up for analysis and proper understanding of harmonious working of power or distribution systems and the presently used non-linear loads in industries by various consumers. These are discussed here in detail.

TECHNICAL ISSUES, ANALYSIS, AND UNDERSTANDING

The TDD (Total Demand Distortion) as specified by IEEE 519 (1992) standard above is with respect I_L. This I_L can be considered as maximum load current available based on sanctioned load. Thus, if the load is less than this I_L (generally for which the current harmonic measurements are likely to be taken), the TDD calculated for this lower load current should be considered more than specified TDD. Consider the following example to appreciate the argument.

Assume 100 kVA load sanctioned at three-phase, 415 V, 50 Hz. The I_L will be 139.12 A. Assume now actual load is 75 kVA. The load current is 104.34 A. Both are fundamental currents at 50 Hz. Further assume harmonics 5th and 7th to have equal values of 1%. Considering current TDD limit as 3%, individual harmonic limit as 1% and full load current of 139.12 A, the absolute values of the harmonics work out as below.

5th harmonic: 1.3912 A RMS
7th harmonic: 1.3912 A RMS
Others considered together: 3.68 A RMS

Table -1 below indicates values of these harmonics as percentage of full load RMS current at 100 kVA (139.12 A) and at 75 kVA (104.34 A).

Table -1: Current TDD at 100 and 75 kVA load

Limits: TDD 3%, Individual harmonic 1%

Parameter	**At 139.12 A full load current**	**At 104.34 A load current**
5th	1.3912 A (1% of 139.12 A)	1.3912 A (1.333% of 104.34 A)
7th	1.3912 A (1% of 139.12 A)	1.3912 A (1.333% of 104.34 A)
Others	3.68 A (2.645% of 139.12 A)	3.68 A (3.527% of 104.34 A)
Total TDD	3% of 139.12 A	3.999% of 104.34 A

Further, same absolute value harmonic currents are also assumed to be present at 75 kVA load current (104.34 A RMS). Thus, their percentages are also given with respect to the actual load current at 75 kVA (104.34 A RMS). The Table also indicates the TDD in both the cases.

The same exercise is also done considering the current TDD limit as 5% as per IEEE 519 (1992) standard, Table 10-3 given in Annexure – A and individual harmonic limit as 1%. The results are given in Table -2. Incidentally, the current TDD limit of 5% is same as specified in IEEE 519 (2014) standard, Table -2 for voltages ≤ 69 kV.

Thus, while measuring the current harmonics at 75 kVA, as in the example (or for load lesser than the full load in general), the individual current harmonic percentage as well as TDD will be and also can be higher.

Table -2: Current TDD at 100 and 75 kVA load

Limits: Current TDD 5%, Individual harmonic 1%

Parameter	**At 139.12 A full load current**	**At 104.34 A load current**
5th	1.3912 A (1% of 139.12 A)	1.3912 A (1.333% of 104.34 A)
7th	1.3912 A (1% of 139.12 A)	1.3912 A (1.333% of 104.34 A)
Others	6.672 A (4.796% of 139.12 A)	6.672 A (6.3945% of 104.34 A)
Total TDD	5% of 139.12 A	6.667% of 104.34 A

Hence, current harmonic and TDD considerations should be as follows.

- Calculate 1% value at full load current (sanctioned load).
- Measured value of any harmonic at any load (less than or equal to full load current) should not exceed this value.
- Measure actual harmonics and TDD at any load current. Calculate the TDD with these harmonic values, not on the basis of the

given load current but on the basis of full load current. This value should be lower than 3% considering the specifications or 5% considering the IEEE 519 (1992) standard as it is also a part of referred standard.

POWER LOSS DUE TO LOWER SHORT CIRCUIT CAPACITY OR I_{sc} / I_L RATIO AT THE PCC

If IEEE 519 (1992) standard has to be given due consideration, then the actual percentage of current harmonics (individual as well as total) is as given in Table 10-3 in Annexure – A (same as Table -2 of IEEE 519 (2014) standard) . This value depends upon the ratio of Short Circuit Current (at the PCC) I_{sc} and the maximum fundamental load current I_L derived from the sanctioned load kVA and supply voltage.

If Utility specifies current THDI (Total harmonic Distortion for Current) or TDD as 3%, looking at the IEEE recommendation, the I_{sc} / I_L ratio is expected to be lesser than <12 and could be assumed as (=20*3%/5%) by simple extrapolation. This means the short circuit capacity at the PCC is further low and the supply network is further becoming weak. This is “against” the interest of the consumer as even the sanctioned fundamental load kVA demand may not be satisfied because of PCC voltage variation (PCC voltage reducing) caused by the fundamental load current itself and as is shown over here by an example.

Consider the same example of load sanctioned as 100 kVA at three-phase 415 V, 50 Hz. The rated current is 139.12 A. Assume the ratio I_{sc} / I_L as 20 (as per IEEE 519 (1992) standard). The short circuit current works out as 2782.4 (=20*139.12) A. The short circuit impedance or inductance works out as 274.69 µH. The supply loss resistance is assumed as 10% of short circuit impedance 0.08625 Ω (=2π*50*274.69*10^{-6}), and hence is 0.008625 Ω. The power deliverable is 99.3 kW at close to Fundamental Unity Power Factor (FUPF). This is the fundamental power factor for linear / sinusoidal loads, normally understood as

Fundamental power factor

= Watts delivered by supply / VA delivered by supply (1)

Actual definition for fundamental power factor is

Fundamental power factor

= Watt hours delivered by supply over a period of time / VA hours delivered by supply over the same period of time (2)

Usually for utilities this period is one month.

For a non-linear / non-sinusoidal loads, what is applicable is overall power factor due to the presence of harmonics in supply currents. The overall power factor is then given by [3]

Overall power factor

= [Fundamental power factor as described above] * Distortion factor of the supply current (3)

The distortion factor for the supply current is given as

Distortion factor for supply current

$$= I_1 / I \tag{4}$$

where

I_1 is the RMS of fundamental current and I is the RMS of the total current.

The correlation between the two RMS currents is given by

$$I^2 = I_1^2 + \sum I_n^2 \tag{5}$$

where In is the “nth” harmonic current present in the supply current.

<u>For all the above equations, the three-phase supply voltages are assumed to be equal.</u>

If the ratio I_{sc} / I_L is considered as 12, the short circuit current works out as 1669.5 A. The short circuit impedance or inductance works out as 457.8 µH. The loss resistance is assumed as 10% of the short circuit impedance 0.14375 Ω and hence is 0.014375 Ω. The power deliverable is

98.25 kW at close to FUPF. Thus, there is a short fall 1.05% (= [99.3-98.25]*100/99.3) of power at FUPF as the terminal voltage goes down.

Similarly, if the ratio I_{sc} / I_L is considered as 6, the short circuit current works out as 834.75 A. The short circuit impedance or inductance works out as 915.64 µH. The power deliverable is 96.1 kW at close to FUPF. Thus, there is a short fall 3.22% (= [99.3-96.1]*100/99.3) of power at FUPF as the terminal voltage further goes down.

Please note that the above results for kW are based on simulating the three-phase system model with balanced load and with different short circuit inductances and resistances in Matlab with Simulink platform.

Thus, the absolute power loss will be higher at higher sanctioned loads with short circuit capacity or ratio I_{sc} / I_L going down.

CORRELATION AMONGST VOLTAGE DISTORTION, CURRENT DISTORTION, AND SHORT CIRCUIT RATIO

In continuation of the same example given above, if the ratio I_{sc} / I_L falls down from 20 to 12, it means short circuit impedance is increasing or short circuit capacity is decreasing. Increased short circuit impedance will mean higher Voltage Harmonic Distortion for the same absolute current harmonics, as the THDV (Total Harmonic Distortion for Voltage) is calculated as below.

$$THDV = [\sqrt{\Sigma(\omega * L_s * n * I_n)^2}\ ] / V_1 \qquad (6)$$

Where

ω = Angular frequency (=2*π*f)

f= Fundamental supply frequency (=50 Hz)

L_s = Short circuit inductance of the supply

n= Harmonic number (≠ 1but >1)

I_n = RMS "n^{th}" harmonic current

V_1 = RMS fundamental supply voltage

As per Table 11-1 of IEEE 519 (1992) standard, as given in Annexure - A, the voltage distortion limits are 3% for individual harmonic and 5% for Total harmonic Distortion for voltages up to 69 kV (IEEE 519 (2014) standard allows these figures as 5% and 8% respectively for voltages ≤ 1 kV). This is without any consideration for voltage harmonic distortion at "no load" at the PCC. If there is already some distortion available in the supply at "no load" condition, the total voltage distortion with load can go higher and cause problems to other connected loads on the same bus, even though the consumer is within limits.

It is hence necessary to understand the correlation amongst various entities, especially the voltage distortion, current distortion and short circuit ratio.

Similar to equation (6) for voltage distortion, the current distortion is as given below.

$$THDI = [\sqrt{\Sigma I_n^2}\ ] / I_1 \qquad (7)$$

where I_1 is the fundamental current.

Considering voltage distortion limit as specified by IEEE 519 (1992 / 2014) standard and already available voltage distortion on the bus, the maximum voltage distortion that can be contributed by the load is governed by the following equation (8).

$$[V_{THD1}]^2 – [V_{THD2}]^2 = \Sigma n^2 * \omega^2 * L_s^2 * I_n^2 / V_1^2 \qquad (8)$$

where ω, L_s, n and V_1 are as defined earlier and other parameters are as given below.

V_{THD1} = Voltage distortion limit in p. u., specified by IEEE 519 (1992) standard

V_{THD2} = Voltage distortion, in p. u., already available at the PCC and on "no load" in utility supply

The equation (8) shows that the voltage distortion at the supply bus not only depends up on the distortion contributed by consumer, but also depends upon already available voltage distortion at the bus. It is directly proportional to the individual current harmonics contributing the current distortion and the short circuit inductance.

Thus, lower short circuit inductance or higher short circuit capacity will mean lower voltage distortion. Other way round, for a given voltage distortion limit and already available voltage distortion at the bus at “no load” condition, the specified current distortion from the consumer can demand considerably lower short circuit inductance or higher short circuit capacity at the PCC.

An example below throws light on this issue.

Considering the earlier / same 100 kVA example, if the voltage distortion limit is 5%, current distortion to be considered is 3%, and only 5th and 7th current harmonics are present in the load, the maximum short circuit inductance acceptable could be 201.39 μH based on equation (8). For this condition and from the same equation, the short circuit capacity required is 27.11 times (100 * 27.11 = 2711 kVA) or the I_{sc} / I_L ratio should be greater than 27.11. This inductance of 201.39 μH is lower than 274.69 μH for I_{sc} / I_L ratio of 20 and 457.8 μH for I_{sc} / I_L ratio of 12. It should be noted that this calculation considers zero voltage distortion at the supply bus at “no load” condition.

The example shows that there is a definite relation between the (specified) current distortion limit which is governed by already available voltage distortion, voltage distortion limit considered as per IEEE 519 (1992 / 2014) standard, and the short circuit capacity (or inductance or the I_{sc} / I_L ratio). Hence, the current distortion specification limit looses its importance if the already available distortion and the short circuit capacity (or inductance or the I_{sc} / I_L ratio) are not specified.

Thus, guidelines as per IEEE 519 (1992) standard (and now its latest version of 2014) for current distortion limits vis-à-vis short ratio I_{sc} / I_L become more relevant and mere specification of 3% current distortion along with 1% individual current distortion is not complete. If both, the utility and the consumers adhere to guidelines as per IEEE 519 (1992 / 2014) standard, there should be a good possibility of harmonious working of various non-linear loads without causing undue disturbances to the electric power or the electric supply system.

QUALITATIVE ARGUMENT ON PROTECTION ISSUES

Lower short circuit capacity not only causes higher voltage distortion but also exerts a constraint on the current harmonics as can be seen from the Tables 10-3 and 10-4 of IEEE 519 (1992) standard (or equivalent Tables of IEEE 519 (2014) standard) given in Annexure - A.

Lower the short capacity, lower is the short circuit current. This means fuses employed for short circuit protection in the incoming supply may not clear the short circuit faults. For proper blowing of the fuses or clearing of the short circuit fault, the fuses need to see a very fast rising current which will meet the clearing I^2t in a very small time of <10 msecs. Thus, selection of fuse with necessary clearing I^2t will become more difficult. This is true for semiconductor high speed fuses as well as for High Rupturing Capacity (HRC) fuses.

If the short current is low in magnitude due to lower short circuit capacity, the fuse instead of blowing will start pre-arcing and can undergo changes in its characteristics. In a worst scenario, it may sustain the fault in short circuit condition and can lead to fire at the installation. This is dangerous and should be avoided. Healthy short circuit capacities involve the I_{sc} / I_L ratio $\geq$ 20. The above explanation and requirements are also true for MCCB’s or ACB’s in incoming supply used for short circuit protection as they also work on similar principle.

It is true that one can still select a fuse under such conditions of low short circuit ratio. However, to ensure that the fuse protects the installation under short circuit condition, the fuse thermal rating will be much lower than the one to be used for rated capacity of the installation. This will mean that the fuse thermal rating will now dictate the installation power capacity, which could be much lower than the sanctioned load capacity or utilizable load capacity. The consumer is deprived of using full rated sanctioned capacity in such a situation.

OTHER ISSUES

It is important to have the short circuit to rated current ratio I_{sc} / I_L as high or as close to at least 22. Many a times this ratio at PCC may not be specified or may not be known to a consumer. A simple procedure to know the same is to establish the short circuit inductance / capacity at PCC. This can be done by a simple experiment and the same is explained in Annexure – B. Once short circuit inductance is know, the short circuit current can be calculated and hence the ratio I_{sc} / I_L can be established.

An equivalent circuit showing supply voltage along with its distortion contributing voltage(s), short circuit inductance, filter capacitor / filter(s) along with a non-linear load is shown in fig. 1.

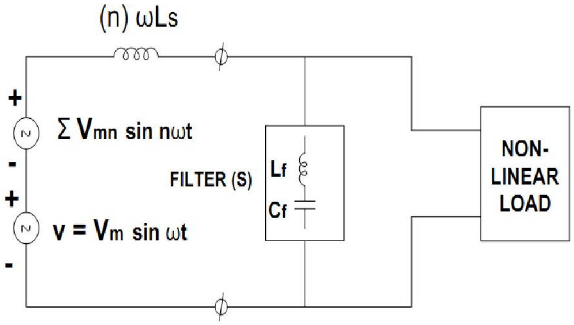

Figure 1: Equivalent circuit considering incoming voltage distortion

From the fig. 1 it is clear that if there is an incoming voltage distortion, it can result in an additional harmonic frequency current (based on frequency of the harmonic(s) contributing the voltage distortion) in the filter capacitor if not properly considered while designing the filter(s). Alternatively it also means, the filter(s) should be designed in such a way that they are detuned for the harmonic(s) contributing to the supply voltage distortion. It is further necessary to carry out a check for the resonance of filter capacitors along with the filter inductance and supply short circuit inductance. A typical model is shown in fig. 2.

This model considers all the system components along with the supply short circuit inductance. The model can be simulated with the help of necessary harmonic current sources to check for no resonance condition using Matlab with Simulink platform.

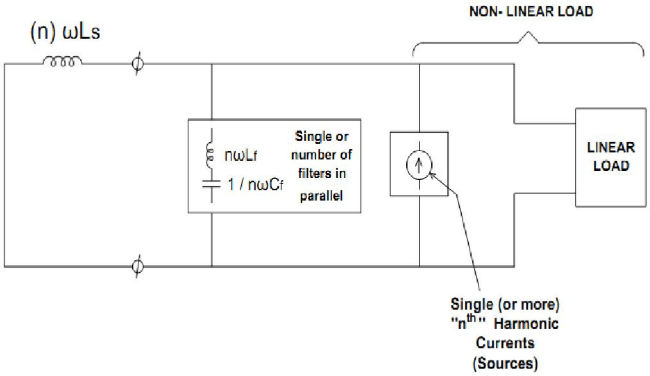

Figure 2: Circuit / model for resonance check

CONCLUSION

It is clear that the supply short circuit capacity at the PCC plays the most important role while considering the voltage distortion caused by the injected harmonics by consumer's non-linear loads. The short circuit capacity virtually dictates stiffness or weakness of the power systems at PCC and it becomes a major part of understanding of the tandem working of non-linear loads with utility power / supply system.

IEEE 519 (1992 / 2014) is a standard which explains effects of connecting a non-linear load with the utility power / supply system and allows both the utility and the consumer to take proper remedial action on individual part. The standard, if followed with proper understanding by both utilities and the consumers, will help in reducing network distortion effects (current as well as voltage), the most important aspect of power or supply system functioning healthily. This will also give an opportunity for both to understand their respective obligations and work towards a better electric system.

Annexure - A

IEEE 519 (1992) relevant information on harmonic control

Table 10-3
Current Distortion Limits for General Distribution Systems (120 to 69000 Volts). Maximum Harmonic Current Distortion in percent of I_L. Individual harmonic number (odd harmonics)

I_{sc}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 10-4
Current Distortion Limits for General Sub-transmission Systems (69001 to 161000 Volts) Maximum Harmonic Current Distortion in percent of I_L. Individual harmonic number (odd harmonics)

I_{sc}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100<1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10

Table 11-1
Voltage Distortion Limits

Bus voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

Notes:

(1) Table 10-3 and Table 10-4 are same as Table -2 and Table -3 of IEEE 519 (2014) standard.

(2) Table 11-1 is similar to Table -1 of IEEE 519 (2014) standard which additionally now allows individual harmonic voltage distortion up to 5% and total voltage distortion up to 8% for voltages ≤ 1 kV.

Annexure – B

Establishing short circuit inductance / capacity of supply network

Figure B1 shows a single-phase source (considered as part of star connected three-phase source) with nominal RMS voltage as "V" with L_s as its short circuit inductance and disconnected form a serving linear / non-linear load. It also shows a capacitor C with its small internal loss resistor R_{loss}. The RMS voltage at terminals "a" and "b" is first measured with both "S_1" and "S_2" switches in off condition. This is called as V_{T1}. The capacitor is then switched on closing the switch "S_1". Once again the terminal RMS voltage (now across the capacitor) is measured as V_{T2} along with the established RMS current "I".

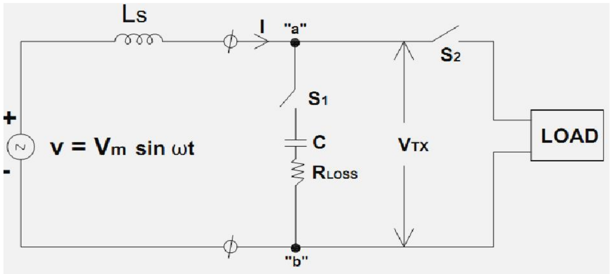

Figure B1: Circuit for establishing the short circuit inductance of supply

The short circuit inductance is now given by following equation (considering R_{loss} is very small compared to the capacitive impedance $1/[C^*\omega]$).

$$L_s = [V_{T2} – V_{T1}] / (I^*\omega) \qquad (B1)$$

where

$\omega = 2 * \pi * f$ (B2)

and

f= Supply frequency (nominal 50 Hz)

For arriving at better and practical value of L_s, the current “I” should be at least 20% of the rated capacity of the supply and many readings in a similar way may have to be taken for calculating the average L_s.

For a three-phase supply, the short circuit capacity SC in MVA then can be calculated as

$\text{SC MVA} = 3 * V^2 * 10^{-6} / (\omega * L_s)$ (B3)

where V is the phase to neutral voltage.

REFERENCES

[1] “Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems,” IEEE 519 standard, 1992.

[2] “Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems,” IEEE 519 standard, 2014.

[3] W. Mack Grady and R. J. Gilleskie,” Harmonics and how they relate to power factor,” Proc. EPRI Power Quality Issues & Opportunities Conference (PQA’93) San Diego, CA, Nov. 1993.