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An Equivalent Voltage Index to Quantify the Impact of Harmonics on Shunt Capacitors

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Abstract. Harmonic distortions are known to affect the normal operation and life of power equipment. Shunt capacitor is one piece of equipment that is very sensitive to harmonics. Although limits have been established to limit the harmonic distortions experienced by a capacitor, methods to quantify the harmonic impact with easy-to-understand indices are still at large. This paper aims to address the above gap by proposing an equivalent voltage index. This index is to represent the impact of harmonic voltages and their features (such as peak value) into an equivalent increase in the fundamental frequency voltage otherwise experienced by the capacitor. The main advantage of such an equivalence is that PQ and non-PQ engineers can easily relate the impact to the general capacitor loading concept. The index is especially helpful to understand the impact of harmonics on capacitor and thus to justify harmonic mitigation projects.

Key words. Harmonics, Capacitor, Harmonic Impact.

1. Introduction

Shunt capacitors are widely used in power systems for voltage support and power factor correction. They are one important type of asset for utility companies. The presence of harmonic voltages and currents can accelerate capacitor degradation. There is, therefore, a need for assessing harmonic impact on capacitors. Several research works have been published on the subject. For example, [1] presented an extensive survey on the work done in the area. According to the findings of the report, partial discharge is the major mechanism of capacitor life degradation. Statistical analysis showed that the prevailing factor responsible for aging is the peak voltage, rather than current or rms voltage of capacitor. However, these findings have not been transformed into intuitive and practical indices that can help a utility engineer to quantify the impact of harmonics on capacitors.

This paper aims to address the above need, i.e. to establish an index that can quantify the impact of harmonics on capacitors. The index should be understandable by non-power quality engineers so that they can relate the harm done by harmonics on a capacitor to the general equipment overloading concept. The results can be used by utility PQ engineers, for example, to convince management to support harmonic mitigation projects.

The proposed index, called equivalent voltage index, can be illustrated as follows: The negative effect of harmonics on shunt capacitors is mainly related to harmonic voltage-caused reduction of capacitor insulation life. If a capacitor experiences a 1.0pu voltage at fundamental frequency only, everyone understands that the capacitor operates at a rated voltage and carries a rated load. If this capacitor also experiences a 2% harmonic voltage on top of its 1.0pu fundamental frequency voltage, it is difficult for PQ and non-PQ engineers to relate the 2% harmonic distortion to the impact on capacitor quantitively. The proposed index will show that the capacitor is experiencing, for example, an equivalent 1.12pu fundamental frequency voltage. It means the effect of the 2% harmonic voltage is equivalent to running the capacitor at 1.12pu fundamental frequency voltage. In other words, the 2% harmonic voltage is equivalent to increasing the fundamental frequency voltage by 12% or the capacitor is over-loaded by 12%. Such an index is much easier to be appreciated by non-PQ engineers especially utility management who makes decisions on if harmonic mitigation projects should be approved.

The rest of this paper is to show the development of such an equivalent voltage index and its application examples. The paper is organized as follows. Section 2 reviews impact of harmonics on shunt capacitors and identify the key factor for index development. Section 3 introduces the proposed equivalent index along with an illustrative example. Section 4 presents case study results including the assessment of an actual shunt capacitor.

2. Harmonic Impacts on Capacitors

Power capacitors are universally the film capacitor type. Film capacitors use an insulating plastic film as the capacitor's dielectric material. The electrical characteristics and the temperature behavior of film capacitors are essentially determined by the film material. Film capacitors are subject to small but measurable aging processes. The primary degradation process is a small amount of plastic film shrinkage, which occurs mainly during the soldering process, but also during operation at high ambient temperatures or at high load. The permissible changes of capacitance, dissipation factor and insulation resistance vary with the film material and are specified in the relevant data sheet. Variations over the course of time which exceed the specified values are considered as a degradation failure. According to literature survey, the two main reasons for capacitor insulation ageing are 1) increased energy losses and overheating and 2) dielectric breakdown due to partial discharge effect.

A. Increased Energy Losses and Overheating

The energy losses in a capacitor include two components, dielectric losses and Joule losses. The former is associated with the energy losses in the insulation materials and the latter is related to losses in the metallic parts of the capacitor. With the presence of harmonics, both losses will increase. Since the reactance of a capacitor is inversely proportional to frequency, the capacitor current will increase with supply voltage harmonics. As a result, a capacitor usually acts like a harmonic sink. This trends to overload the capacitor and increase the heating and dielectric stress of the insulation materials. When harmonic resonance occurs, capacitors will experience much higher harmonic voltages. The overheating effect will become more harmful to the capacitors.

Most publications presented the qualitative thermal effect of harmonics on capacitors. Quantitative data are not available. One of the main reasons is that partial discharge can also increase capacitor temperature (see next section). It becomes very difficult to separate the two factors. According to [2], the increased losses in capacitors due to harmonics can be calculated as Equation 2-1:

$$L=\sum_{h=2} C\left(\tan\delta\right)_h 2\pi h f V_n^2 \tag{1}$$

where

L	is the increase in losses (W)
h	is the harmonic order
C	is the capacitance
$\left(\tan\delta\right)_h$	is the loss factor under hth harmonic excitation
f	is fundamental frequency
V_h	is rms voltage of the hth harmonic (V)

Strictly speaking, (1) represents only the dielectric losses. The total capacitor losses include Joule losses and dielectric losses. [2] gave expressions of these two types of losses under distorted supply voltage and pointed out that the dielectric losses are prevailing in comparison to Joule losses. Therefore, it is acceptable to approximate the additional harmonic-caused losses using (1).

B. Dielectric Breakdown Due to Partial Discharge Effect

In general, the effect of voltage distortion on insulation degradation is associated with thermal aging. However, it was found that the temperature increase due to dielectric and resistive losses within the capacitor body is not sufficient to explain the accelerated aging of the capacitor insulation [3]. Partial discharge or corona due to high electrical field level plays a predominant role in capacitor insulation degradation. If the electric field is high enough, partial discharge can occur in the capacitor insulation, leading to a higher thermal stress across the insulation of the capacitor. Statistical analysis showed that the prevailing factor responsible for capacitor partial discharge is voltage, rather than current (i.e. losses associated with Equation (1)).

Laboratory tests and statistical analysis were conducted to determine the cause of insulation degradation. G.C. Montanari, A. Cavallini, et al. published a series of papers on capacitor insulation failure investigations ([4]-[7]). The tests were done on two capacitor insulation materials: cross-linked polyethylene (XLPE) and polypropylene (PP). Different voltage distortion levels were applied to the insulation materials to test the life-shortening consequences. The paper found that increase of peak value at constant rms voltage can shorten insulation life significantly for both XLPE and PP. Smaller but non-negligible contributions, in descending order of importance are, rms voltage and voltage slope. The tests also indicated that both XLPE and PP provide endurance coefficient values that are very close to those obtained elsewhere under sinusoidal voltages. That means the prevailing degradation mechanism under distorted voltage waveforms is the same for sinusoidal and non-sinusoidal voltage waveforms. Reference [7] provided an example to show the voltage rms value is much less important than peak value for insulation lifetime shortening. Based on these findings, lifetime models for capacitor insulation materials are derived in [4] as shown in (2) below:

$$\ln L=\ln L_0-n_pK_p-n_{rms}K_{rms}-n_fK_f \tag{2}$$

where

L	is the lifetime of capacitor insulation
L_0	is the reference lifetime of capacitor insulation
n_p, n_{rms} and n_f	are coefficients that describe the significance of each factor. Their values are dependent on the type of films used in the capacitor
K_p, K_{rms} and K_f	are indices describing the waveform experienced by the capacitor, as follows

$$K_p=\frac{V_p}{V_{1p}^*} \tag{3}$$

$$K_{rms}=\frac{V_{rms}}{V_{1rms}^*} \tag{4}$$

$$K_f=\sqrt{\sum_{h=1}^{N} h^2\left(\frac{V_h}{V_1}\right)^2} \tag{5}$$

where

V_p	is the peak value of the distorted voltage
V^*_{1p}	is the peak value of the rated fundamental frequency voltage
V_{rms}	is the rms value of the distorted voltage
V^*_{rms}	is the rms value of the rated fundamental frequency voltage
h	is the harmonic order.

K_p, K_{rms} and K_f describe the peak, rms and “slope” of the waveform respectively. It is noteworthy that the indices become 1 for a purely sinusoidal waveform at the supply-frequency. In [7], these equations were developed as a reliability model to achieve time-to-failure estimates at selected probability levels for given stress values applied to the insulation system.

C. Summary

Harmonics have two main effects on the operation of capacitors. The first one is increased losses and the second one is the reduction of insulation material life caused by the partial discharge effect. Both effects are functions of harmonic voltages. Since capacitors have small dielectric and Joule losses, the increased heating due to these losses and associated insulation life reduction are not significant. On the other hand, the partial discharge effect is more pronounced in terms of reduced insulation life. Partial discharge of capacitor insulation increases because of harmonic voltages could increase the peak voltage experienced by the capacitor.

3. Equivalent Voltage Index

IEEE standard 18-2002 and IEEE 1036-2010 have established limits on the voltage, current and reactive power applied to a capacitor bank. They can be used to determine the maximum allowable harmonic levels. The standard indicates that a capacitor can be operated continuously within the following limits:

a) 110% of rated rms voltage
b) 120% of rated peak voltage
c) 135% of nominal rms current
d) 135% of rated kvar

In theory, the above limits could be used to quantify the overloading level of a capacitor. However, this approach has several disadvantages. Firstly, there are four indices to define the limits. A method needs to be developed to combine these indices into a single index. Secondly, these indices do not easily lead to the establishment of a base loading level that can be used to compare the impact of different harmonics on a capacitor. Therefore, a new index is proposed here to qualify the loading level of a capacitor based on research findings of partial discharge caused capacitor aging [4].

A. Equivalent Voltage Index of a Capacitor

A capacitor is typically a shunt-connected device and this paper deals with such capacitors. The voltage applied to the shunt capacitor is the only variable needed to establish the loading level of the capacitor, as the capacitor current and VAr output can be calculated from the voltage. Furthermore, the voltage applied to the capacitor has the most significant impact on the degradation of the capacitor. It is, therefore, natural to use voltage to establish the stress level applied to a capacitor.

Equation (2) is a lifetime model for capacitor insulation materials. It can be rewritten in the form of (6):

$$L = L_0 \cdot \frac{1}{\left(K_p\right)^{n_p} \cdot \left(K_{rms}\right)^{n_{rms}} \cdot \left(K_f\right)^{n_f}} \tag{6}$$

The above equation reveals that term $\left(K_p\right)^{n_p} \cdot \left(K_{rms}\right)^{n_{rms}} \cdot \left(K_f\right)^{n_f}$ represents the ratio of life reduction for a capacitor. For example, if $\left(K_p\right)^{n_p} \cdot \left(K_{rms}\right)^{n_{rms}} \cdot \left(K_f\right)^{n_f} = 1.1$, Equation (3-1) gives $L=0.909L_0$, meaning that the life of the capacitor is reduced by 9.09%. Furthermore, if the capacitor operates at the rated, pure-sinusoidal voltage, this term is equal to one. There is no life reduction in this case. The higher of this term, the more degradation of life the capacitor will experience. Therefore, the above term can be used to describe the stress (or loading) experienced by a capacitor. An equivalent voltage index is then proposed as follows:

$$V_{eq-pu} = \left(K_p\right)^{n_p} \cdot \left(K_{rms}\right)^{n_{rms}} \cdot \left(K_f\right)^{n_f} \tag{7}$$

Note that the above index is called equivalent voltage as the terms K_p, K_{rms} and K_f are all related to the voltage experienced by the capacitor. The physical meaning of this index is that it represents a normalized, equivalent voltage applied to a capacitor. If the voltage is above one, the capacitor is considered as overloaded, and its life will be shortened. If the value is less than one, the capacitor is considered as operating within its design limits. The range of this index is from 0 to positive infinity.

The coefficients n_p, n_{rms} and n_f used in the above definition are highly dependent on the capacitor insulation materials, but the relative values among them are consistent. For example, peak voltage is always the dominant factor and has a much higher weight among the three coefficients. Table 1 shows typical values of n_p, n_{rms} and n_f for XLPE and PP material [4]. Since XLPE is commonly used for power distribution capacitors, the corresponding coefficients will be used for subsequent case studies.

Table 1: Typical capacitor aging coefficients

Insulation material	n_p	n_{rms}	n_f
XLPE (Cross-linked polyethylene)	14.3	4.7	1.3
PP (Polypropylene)	5.3	2.0	0.8

B. Quantifying the Impact of Harmonics on Capacitor

Two factors can cause the equivalent voltage of a capacitor to be higher than 1. One is that the capacitor operates at a pure-sinusoidal voltage that is higher than rated fundamental frequency voltage. Another is that it experiences harmonic voltages. Definition Eq. 7 has included both the effects of fundamental frequency voltage and harmonic voltages. To quantify the impact of harmonics alone on the capacitor loading, the following procedure is proposed.

When a capacitor experiences a voltage that consists of a fundamental frequency component (V_1) and harmonics (V_h), the stress imposed on the capacitor can be characterized using $V_{eq\text{-}pu}$ as explained in the previous section. If the voltage contains the fundamental frequency voltage of V_1 only, the corresponding equivalent voltage is $V_{eq\text{-}pu1}$. This voltage can be derived as follows based on equations (3) to (5):

$$V_{eq-pu1} = \left(\frac{V_1}{V_{1rms}^*} \right)^{n_p + n_{rms} + n_f} \tag{8}$$

The above equivalent voltage can be less than 1.0 if the actual capacitor (fundamental frequency) voltage is less than the rated voltage.

It can be seen that harmonics have caused the equivalent voltage, i.e. the stress on the capacitor, rises from $V_{eq\text{-}pu1}$ to $V_{eq\text{-}pu}$. The impact of harmonics can thus be characterized by using either the increase of the voltage index, i.e. $V_{eq\text{-}pu} - V_{eq\text{-}pu1}$ or the ratio of the index $V_{eq\text{-}pu}/V_{eq\text{-}pu1}$. Since the latter has a more direct physical meaning associated with the capacitor life (as explained below), it is selected as the index to characterize the impact of harmonics, i.e.

$$\text{Harmonic impact factor (HIF)} = \frac{V_{eq-pu}}{V_{eq-pu1}} \tag{9}$$

Since the equivalent voltage is related to the capacitor life,

$$L = L_0 \frac{1}{V_{eq\text{-}pu}} \quad and \quad L_1 = L_0 \frac{1}{V_{eq\text{-}pu1}} \tag{10}$$

HIF is also related to capacitor life as follows:

$$HIF = \frac{V_{eq-pu}}{V_{eq-pu1}} = \frac{L_0 / L}{L_0 / L_1} = \frac{L_1}{L} \tag{11}$$

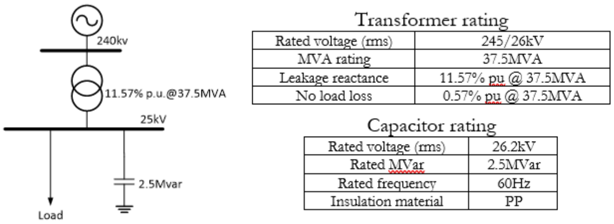
The meaning of the above equation is that *HIF* also represents the ratio of capacitor life increase (improvement) if there were no harmonics in the waveform.

C. Procedure to Calculate the Indices

The overall method to quantify the impact of harmonic voltages on a shunt capacitor, i.e. the equivalent voltage it experiences, can be summarized as fellows:

1) The capacitor voltage, including voltage harmonics, is either measured from field or calculated using harmonic power flow programs, depending on if the capacitor has been in operation or if it is being planned for installation.
2) Calculate K_p, K_{rms} and K_f based on equation (3) to (5) from the measured or calculated capacitor voltage. Capacitor peak voltage can be obtained from the voltage waveform directly. RMS voltage and voltage slope can be calculated from voltage spectrum.
3) Calculate capacitor loading indices, $V_{eq\text{-}pu}$, $V_{eq\text{-}pu1}$, and *HIF* using Equations (7)-(9)

As an illustrative example, the proposed capacitor loading indices - capacitor equivalent voltage '$V_{eq\text{-}pu}$' and harmonic impact factor '*HIF*', are employed for loading assessment of a shunt capacitor shown in Fig. 1.



Transformer rating

Rated voltage (rms)	245/26kV
MVA rating	37.5MVA
Leakage reactance	11.57% pu @ 37.5MVA
No load loss	0.57% pu @ 37.5MVA

Capacitor rating

Rated voltage (rms)	26.2kV
Rated MVar	2.5MVar
Rated frequency	60Hz
Insulation material	PP

Fig. 1: Example shunt capacitor and related data.

<u>Step 1: Acquire capacitor voltage.</u> In this case, the capacitor voltage at each harmonic is measured and is tabulated in Table 2. Capacitor voltage waveform can be reconstructed with the voltage spectrum. Voltage peak can be obtained directly from the waveform.

Table 2: Measured capacitor voltage spectrum

Harmonic order	Capacitor voltage spectrum (V)
1	$25994\angle -119.31^\circ$
5	$391.23\angle 58.34^\circ$
7	$146.23\angle 30.66^\circ$
11	$647.04\angle 7.23^\circ$
13	$177.75\angle 170.54^\circ$

<u>Step 2: Calculate K_p, K_{rms}, K_f</u>

$$\begin{cases} K_p = \dfrac{V_p}{V_{1p}^*} = \dfrac{37714}{26200 \times \sqrt{2}} = 1.0179 \\ K_{rms} = \dfrac{V_{rms}}{V_{1rms}^*} = \dfrac{\sqrt{25994^2 + 391.2^2 + \cdots + 177.75^2}}{26200} = 0.9926 \\ K_f = \dfrac{\omega_1}{\omega_0} \sqrt{\sum_{h=1}^{N} h^2 \alpha_h^2} = 1.0441 \end{cases}$$

<u>Step 3: Calculate capacitor loading indices.</u> Since the capacitor insulation material is PP (Polypropylene), the coefficients n_p, n_{rms} and n_f can be found in Table 1. Capacitor equivalent voltage '$V_{eq\text{-}pu}$' is calculated as:

$$\begin{aligned} V_{eq-pu} &= \left(K_p\right)^{n_p} \cdot \left(K_{rms}\right)^{n_{rms}} \cdot \left(K_f\right)^{n_f} \\ &= 1.0179^{5.3} \times 0.9926^{2.0} \times 1.0441^{0.8} = 1.12 \end{aligned}$$

Since the equivalent voltage '$V_{\text{eq-pu}}$' is greater than 1. The capacitor is slightly overloaded. Capacitor life is expected to be shortened.

Equivalent voltage without harmonics '$V_{\text{eq-pu1}}$':

$$V_{eq-pu1}=\left(\frac{V_1}{V^*_{1rms}}\right)^{n_p+n_{rms}+n_f}=\left(\frac{25994}{26200}\right)^{5.3+2.0+0.8}=0.9381$$

Harmonic impact factor '*HIF*':

$$HIF=\frac{V_{eq-pu}}{V_{eq-pu1}}=\frac{1.12}{0.9381}=1.1939$$

This index indicates that, before the harmonics are taken into consideration, the capacitor is about 6% (=1-0.9381) under loaded. However, due to the existence of harmonics, especially 11th harmonic caused by parallel resonance, the capacitor voltage is amplified thus leading to overloading. The harmonics produce about 19.39% of extra loading stress to the capacitor.

4. Sensitivity Studies and Applications

A set of sensitivity and case studies are conducted in this section to determine the key factors on capacitor overloading and to illustrate the application of the proposed index.

A. Impact of resonance on capacitor loading

The system shown in Fig. 1 is used for this study. Here the size of the capacitor is varied. This will lead to the change of resonance frequency. The resonance frequency may get closer to or farther away from the 11th harmonic. Accordingly, the equivalent voltage index will have different values. Fig. 2 shows the impact on the equivalent voltage index when the capacitor size is varied. In order to show the impact of resonance, the x-axis shows the resonance frequency instead of the capacitor size (both have one-to-one relationship). It can be seen that if the capacitor size is such that it resonates close to the 11th harmonic, the equivalent voltage will be significantly amplified. For the sample case, the capacitor shall be sized to avoid the range of [11-0.4 11+0.4] that can lead to significant loss of life.

B. Impact of harmonic voltage phase angle

As discussed in the previous sections, capacitor insulation degradation is extremely sensitive to voltage peak. Unlike pure sinusoidal waves, voltage peaks that are distorted by harmonics are affected by both harmonic magnitudes and their phase angles. The harmonic phase angle here denotes the phase angle difference between harmonic and fundamental component. In general, the capacitor has only one resonant frequency. Hence we approximate the voltage experienced by a capacitor as the summation of the fundamental frequency component and the dominant harmonic component. For example, let's consider two cases of

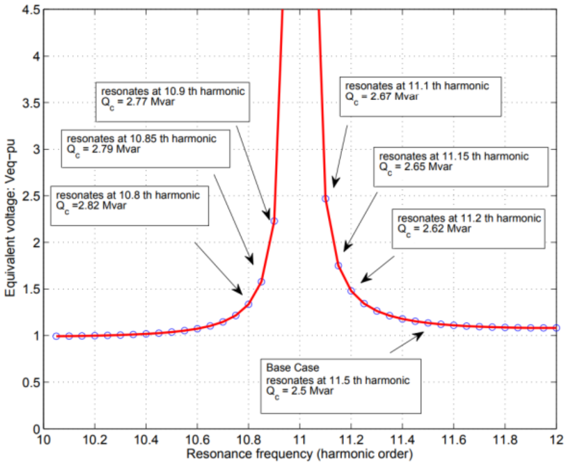


Fig. 2: Impact of resonance on equivalent voltage.

$$v_{case1}=100\cos(\omega t+0^\circ)+5\cos(7\omega t+10^\circ)\ \text{and}$$

$$v_{case2}=100\cos(\omega t+0^\circ)+5\cos(7\omega t+100^\circ)$$

Both cases have the same rms value (K_{rms}) and voltage slope (K_f). However, their voltage peak values have a 10% difference (Fig. 3). The reason for this is that the harmonic and fundamental component may add up or cancel with each other depending upon their phase angle difference.

In Fig. 3, the loading index of the base case vs. its 7th harmonic phase angle is plotted to analyze the impact of phase angle on loading index. As can be seen from the figure, the rms voltage remains unchanged regardless of the phase angle. However, peak voltage changes from 1.01 to as high as 1.55pu, consequently the index changes in the range of 1.1 to 1.4.

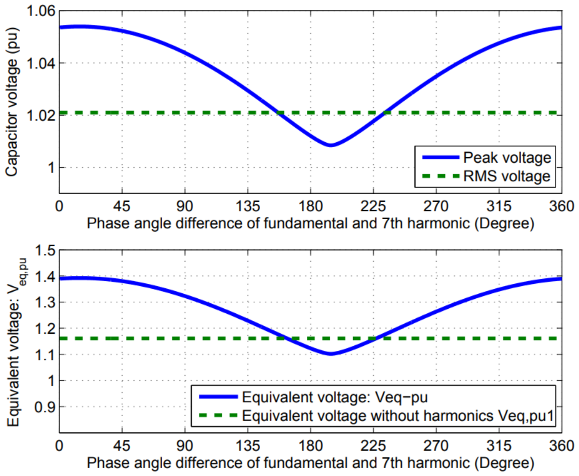


Fig. 3: Impact of phase angle on capacitor peak voltage and equivalent voltage index.

C. Capacitor loading condition of an actual case

In this subsection, loading condition of an actual shunt capacitor is evaluated by the proposed index. A shunt capacitor bank is installed at a substation. The capacitor bank voltage has been continuously measured for several days. The loading indices - equivalent voltage '$V_{\text{eq-pu}}$' and harmonic impact factor '*HIF*' for the capacitor is calculated for all hours of the same day and is shown in Fig. 4.

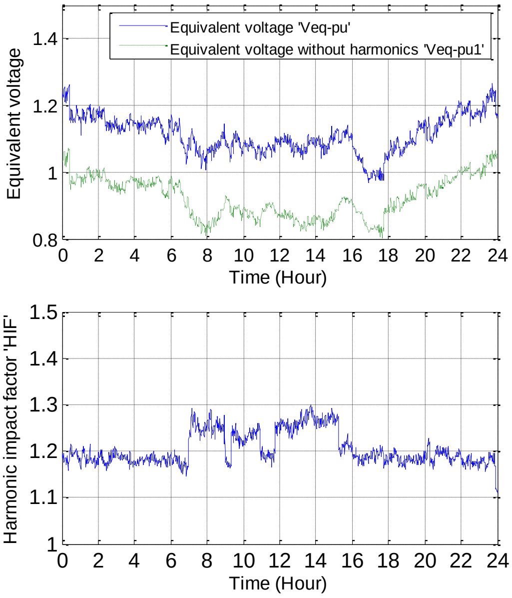


Fig. 4: Capacitor loading indices in 24 hours of a day

Main observations drawn from Fig. 4 are summarized below:

- Equivalent voltage '$V_{\text{eq-pu}}$' is above 1 for all 24 hours. This suggests that the capacitor is overloaded over the entire recording period.
- Harmonic impact factor '*HIF*' can be higher than 1.2 for several hours. It shows that harmonics can indeed have a significant impact on capacitor life by shortening it 20% if the capacitor always operate under such conditions.

5. Conclusions

The impact of harmonics on a shunt capacitor is mainly through the mechanism of partial discharge. The impact can be characterized using the voltage experienced by the capacitor. Based on the life model of capacitor insulation degradation, this paper presents a loading index, called ‘equivalent voltage index’, to quantify the impact of harmonics on capacitors. An equivalent voltage higher than 1pu represents that the capacitor experiences excessive voltage stress. Since the equivalent voltage includes both the effects of fundamental frequency voltage and the harmonic voltage, the index has unified the loading assessment of the capacitor as all voltage components are included. In addition, the impact of harmonics can be estimated from the harmonic impact factor, which is derived from the equivalent voltage index. Based on the indices, the following main findings are obtained:

(1) Capacitors can be easily overloaded by harmonic voltages. Typical loading increase is about 15% based on the field measured voltage waveforms.

(2) The main factor causing capacitor overload is the peak voltage. As a result, phase angles of the harmonic voltages and fundamental frequency voltage must be considered when evaluating capacitor overloading levels.

(3) A capacitor can be made to handle higher harmonic voltage if its rated voltage is increased. For example, a 30kV capacitor can be selected for a 25kV application.

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