A Practical Harmonic Resonance Guideline for Shunt Capacitor Applications

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***Abstract*—Shunt capacitors are extensively used in power systems for voltage support and power factor correction. The proliferation of harmonic-producing loads significantly increases the possibility of system-capacitor resonance. As a result, a practical and easy-to-use procedure to estimate the severity of harmonic resonance is of good interest to industry. The objective of this paper is to present such a method. The paper first proposes a harmonic resonance index. By taking into account the IEEE harmonic limits and the capacitor loading limits, a harmonic resonance chart is developed. A detailed harmonic analysis of the system is needed only if the system condition is located in certain regions of the chart. Examples are given to show how the possibility and severity of harmonic resonance can be estimated using the proposed guideline.**

***Index Terms*—Capacitors, harmonic resonance, harmonics.**

I. INTRODUCTION

APPLICATION of shunt capacitors for voltage support and power factor correction is a common practice in the power industry. With the proliferation of harmonic-producing loads and the increasing awareness of harmonic effects, the possibility of system-capacitor resonance has become a routine concern for shunt capacitor applications [1]–[3]. Whenever a shunt capacitor is to be added or resized, system planners are interested to know if the proposed capacitor installation would resonate with the system and, if there is a resonance, the severity of the problem.

A well-known and commonly practiced method to verify if a capacitor resonates with its supply system is to determine the ratio of the system fault level to the capacitor size [4]. Resonance frequency can be estimated from this ratio. Our experience shows that this method is too crude to be practically useful. The formula is based on the assumption that the system harmonic reactance is proportional to its fundamental reactance determined from the fault level. There is no guarantee that this assumption is valid for practical interconnected power systems. Furthermore, one cannot determine the severity of the resonance as not all resonance conditions will cause problems.

An alternative to the above method is to conduct harmonic power flow study and/or frequency scan study. The harmonic power flow study is too complicated for this task since the locations of harmonic sources and the source characteristics are typically unknown. The frequency scan study [5]–[7] is more useful. It can reveal the resonance frequencies and the associated magnitudes of the combined system-capacitor impedance. The study is easy to do so the engineers who plan the capacitor installation can perform the study.

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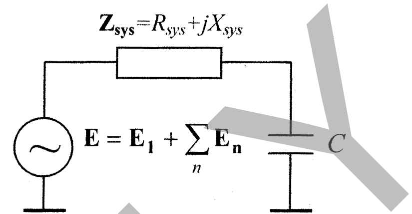

Fig. 1. Equivalent system with capacitor to be installed.

There is one major difficulty to use the frequency scan method however. If the engineers have obtained the impedance $\sim$ frequency curve, how can they draw a conclusion as to the potential harmonic impact of the proposed capacitor? The resonance frequency may or may not coincide with a harmonic order. If it does, the existence of harmonic resonance does not necessarily imply that a problem would occur, since the system resistance may provide sufficient damping to the resonance. If it does not coincide with a harmonic frequency, the system damping may still be too small so a resonance problem could still exist. Furthermore, there is the problem of how to quantify the closeness of a resonance frequency with the harmonic frequency. If the system exhibits multiple resonance frequencies, it becomes more difficult to assess the harmonic impact of the capacitor.

In this paper, methods are proposed to address the above problems. It leads to the development of a practical and easy-to-use harmonic resonance chart. By examining the frequency scan results with respect to the chart, one can quickly determine if the proposed capacitor installation could cause resonance problem. The key idea of the proposed chart is the concept of harmonic resonance index defined as the ratio of the n-th harmonic admittance to the fundamental frequency admittance. If the index is located inside the "safe region" of a guideline chart, no further analysis is needed and the capacitor installation can proceed with confidence. Detailed harmonic analysis is recommended if the index violates the guidelines.

II. CONCEPT OF HARMONIC RESONANCE CHART

Fig. 1 shows the Thevenin equivalent circuit of a power system at the capacitor location and the associated capacitor to be installed. $\mathbf{E}$ and $\mathbf{Z_{sys}}$ are the open-circuit (i.e., background) system voltage and Thevenin impedance, respectively. $\mathbf{Z_{sys}}$ is obtained by frequency scan study [5]–[7]. The total harmonic

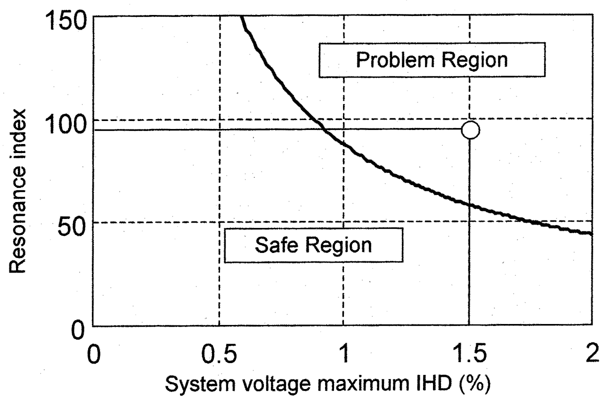

Fig. 2. Sample guideline chart of harmonic resonance index.

impedance is the combination of the system impedance and the capacitor impedance in series. For each harmonic order, the total harmonic admittance can then be calculated and the ratio of the n-th harmonic admittance Y_n to the fundamental admittance Y_1 is defined as the harmonic resonance index

$$RI_n = \frac{Y_n}{Y_1}, \quad \mathrm{n} = 1, 2, 3, \ldots \tag{1}$$

The resonance guideline or chart proposed in this paper is a set of curves whose x-axis is the background voltage individual harmonic distortion (IHD) level (before the capacitor installation) and y-axis the resonance index. Fig. 2 shows the simplest chart that has only one curve. The curve in the chart displays a boundary below which the impact of harmonic resonance can be considered as insignificant, while above which the harmonic resonance could cause a problem. Detailed system harmonic analysis is therefore recommended for the later case.

As an example, assume that the fundamental and the 5-th combined system-capacitor admittances are 0.55 and 52, respectively. By the definition, the resonance index is calculated as 94.55. The system voltage distortion is unknown. The distortion limit of 1.5% established by the IEEE Standard 519 is taken as a conservative estimate. A point (1.5, 94.55) can be found in the problem region of the chart. Thus, it can be concluded that the 5-th harmonic resonance is likely to cause a problem. Consequently, detailed harmonic analysis is recommended to further investigate the resonance problem. The boundary limit for this case is 58, below which no further analysis is necessary.

The boundary curve is established using the capacitor loading limits [7]. The guideline proposed in this paper is therefore developed from the perspective of capacitor concerns. Details on the derivation of the curve are described in the next section.

III. Development of the Proposed Guideline

Referring to Fig. 1, the equivalent system voltage containing harmonics can be expressed as

$$\mathbf{E} = \mathbf{E_1} + \sum_n \mathbf{E_n}. \tag{2}$$

E_n, the magnitude of $\mathbf{E_n}$, is supposed to satisfy the IEEE Standard 519 (voltage level 69$\sim$138 kV) [4]

$$E_n = \alpha_n E_1, \text{ where } \alpha_n \leq 1.5\%. \tag{3}$$

The fundamental components of capacitor current and voltage are

$$I_{C1} = E_1 Y_1, \quad V_{C1} = \frac{I_{C1}}{\omega C} = \frac{E_1 Y_1}{\omega C} \tag{4}$$

where ω is the fundamental angular frequency, C is the capacitor farads, and Y_1 is the fundamental admittance with the capacitor included.

For each harmonic order $n\ (> 1)$, the harmonic components of capacitor current and voltage are

$$I_{Cn} = E_n Y_n, \quad V_{Cn} = \frac{I_{Cn}}{n\omega C} = \frac{E_n Y_n}{n\omega C} \tag{5}$$

where Y_n is the n-th harmonic admittance with the capacitor included.

$$Y_n = \left| \frac{1}{\mathbf{Z_{sys}}(n) + \mathbf{Z_{cap}}(n)} \right| = \left| \frac{1}{R_{sys}(n) + jX_{sys}(n) - j\frac{1}{n\omega C}} \right| \tag{6}$$

where $\mathbf{Z_{sys}}(n)$ is determined by the frequency scan method [5]–[7]. A harmonic resonance condition would exist if

$$X_{sys}(n) = \frac{1}{n\omega C}. \tag{7}$$

Under such a condition, the total combined system-capacitor impedance becomes

$$Y_n = \frac{1}{R_{sys}(n)}. \tag{8}$$

Equation (8) shows that Y_n will be large at resonant frequencies. It also shows that when the capacitor resonates with the system, the system resistance may provide sufficient damping and reduce the harmonic current. Hence, the existence of harmonic resonance does not necessarily imply that the capacitor would be damaged. It is therefore necessary to assess the severity of the resonance condition. The standard loading indices and limits for shunt capacitors [8], shown in Table I, are adopted as a means to quantify the severity. From (4) and (5), the capacitor loading indices can be calculated as

$$\begin{aligned} I_{rms} &= \sqrt{{I_{C1}}^2 + \sum_n {I_{Cn}}^2} \\ &= \sqrt{(E_1 Y_1)^2 + \sum_n (E_n Y_n)^2} \end{aligned} \tag{9}$$

$$\begin{aligned} V_{rms} &= \sqrt{{V_{C1}}^2 + \sum_n {V_{Cn}}^2} \\ &= \frac{1}{\omega C} \sqrt{(E_1 Y_1)^2 + \sum_n \left(\frac{E_n Y_n}{n}\right)^2} \end{aligned} \tag{10}$$

$$\begin{aligned} S &= V_{rms} I_{rms} \\ &= \frac{1}{\omega C} \sqrt{(E_1 Y_1)^2 + \sum_n \left(\frac{E_n Y_n}{n}\right)^2} \\ &\quad \times \sqrt{(E_1 Y_1)^2 + \sum_n (E_n Y_n)^2}. \end{aligned} \tag{11}$$

TABLE I
STANDARD CAPACITOR LOADING INDICES AND LIMITS

Index	Description	Limit
S	Apparent power of the capacitor (= I_{rms} * V_{rms})	135%
V_{rms}	RMS voltage of the capacitor	110%
V_{peak}	Peak voltage of the capacitor	120%
I_{rms}	RMS current of the capacitor	180%

Considering the worst case, the peak value of the capacitor voltage would be the algebraic summation of the fundamental component and all the harmonic components, that is

$$V_{peak}=\sqrt{2}V_{C1}+\sum_n \sqrt{2}V_{Cn}=\frac{\sqrt{2}}{\omega C}\left(E_1Y_1+\sum_n\left(\frac{E_nY_n}{n}\right)\right). \quad (12)$$

According to Table I, the following conditions should be satisfied in order to safely install the capacitor:

$$S \le 135\% S_{rated} \quad (13)$$
$$V_{rms} \le 110\% V_{rms,rated} \quad (14)$$
$$V_{peak} \le 120\% V_{peak,rated} \quad (15)$$
$$I_{rms} \le 180\% I_{rms,rated}. \quad (16)$$

The subscript "*rated*" indicates the rated values of the capacitor, which can be conservatively considered as the fundamental components

$$S_{rated}=V_{C1}I_{C1}=\frac{(E_1Y_1)^2}{(\omega C)} \quad (17)$$
$$V_{rms,rated}=V_{C1}=\frac{E_1Y_1}{(\omega C)} \quad (18)$$
$$V_{peak,rated}=\sqrt{2}V_{C1}=\frac{\sqrt{2}E_1Y_1}{(\omega C)} \quad (19)$$
$$I_{rms,rated}=I_{C1}=E_1Y_1. \quad (20)$$

Combining (3) and (9)–(20) and defining the harmonic resonance index as (1), we have

$$\sqrt{1+\sum_n\left(\frac{\alpha_n}{n}RI_n\right)^2}\sqrt{1+\sum_n(\alpha_nRI_n)^2} \le 135\% \quad (21)$$
$$\sqrt{1+\sum_n\left(\frac{\alpha_n}{n}RI_n\right)^2} \le 110\% \quad (22)$$
$$1+\sum_n\left(\frac{\alpha_n}{n}RI_n\right) \le 120\% \quad (23)$$
$$\sqrt{1+\sum_n(\alpha_nRI_n)^2} \le 180\%. \quad (24)$$

The task now becomes how to find RI_n that can satisfy the above inequality constraints. In the following subsections, approximate methods to estimate RI_n are developed for three different cases.

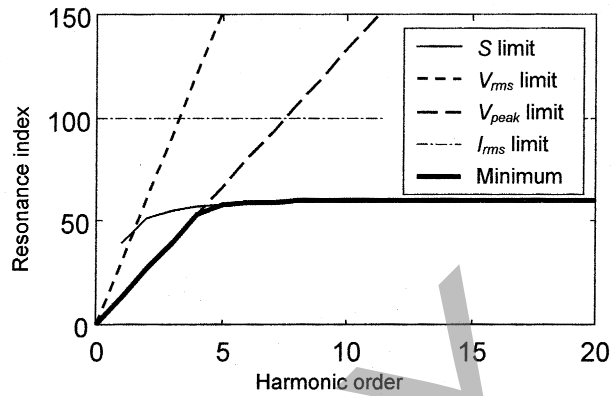

Fig. 3. Harmonic index limit versus harmonic order.

A. Case of a Single Harmonic Component

If the system voltage contains only one harmonic or only one harmonic is dominating (e.g., the n-th harmonic), (21)–(24) can be rewritten as

$$\sqrt{1+\left(\frac{\alpha_n}{n}RI_n\right)^2}\sqrt{1+(\alpha_nRI_n)^2} \le 135\% \quad (25)$$
$$\sqrt{1+\left(\frac{\alpha_n}{n}RI_n\right)^2} \le 110\% \quad (26)$$
$$1+\frac{\alpha_n}{n}RI_n \le 120\% \quad (27)$$
$$\sqrt{1+(\alpha_nRI_n)^2} \le 180\%. \quad (28)$$

In the absence of the voltage distortion information, the E_n is considered to reach its limit in (3) (i.e., $\alpha_n = 1.5\%$). The index RI_n is then obtained by solving (25)–(28) and taking the minimum value as the threshold for avoiding harmonic resonance. The results of RI_n for different harmonic orders are shown in Fig. 3.

From Fig. 3, the following conclusions can be drawn:

1) The I_{rms} limit gives a constant harmonic index limit.
2) The index limit corresponding to the V_{rms} limit is always greater than that corresponding to the V_{peak} limit.
3) Around the 5-th harmonic, the S limit and the V_{peak} limit have similar limits on the harmonic index. For higher order harmonics, the S limit becomes the limiting factor for the harmonic resonance and it yields an almost constant index limit for different harmonic orders.

Since power systems rarely experience harmonics below 5-th, the index limit given by the S limit at the 5-th harmonic, the worst case, can be taken as the general threshold of the case considering a single harmonic.

B. Case of Multiple Harmonic Components

In the case of the simultaneous existence of multiple harmonics, (21)–(24) can be simplified by assuming, conservatively, that RI_n has the same limit, say RI, with different n. In other words, the system resonates at all harmonic frequencies

TABLE II
INDEX LIMITS OF TWO-HARMONIC RESONANCE

Harmonic Order	5	7	11	13
5	-	38.89	41.86	41.90
7		-	42.21	42.25
11	(Same as		-	42.48
13	upper triangle)			-

and the admittance ratios are the same at all harmonic frequencies. The resulting equations are as follows:

$$\sqrt{1+RI^2\sum_n\left(\frac{\alpha_n}{n}\right)^2}\sqrt{1+RI^2\sum_n{\alpha_n}^2}\leq 135\% \quad (29)$$

$$\sqrt{1+RI^2\sum_n\left(\frac{\alpha_n}{n}\right)^2}\leq 110\% \quad (30)$$

$$1+RI\sum_n\left(\frac{\alpha_n}{n}\right)\leq 120\% \quad (31)$$

$$\sqrt{1+RI^2\sum_n(\alpha_n)^2}\leq 180\%. \quad (32)$$

If all harmonics were considered, the above equations would be too conservative. Since the most significant harmonics in power systems are 5-th, 7-th, 11-th, and 13-th, the limit value RI can be derived by including two or more of these harmonics. If we take two of them into consideration, the limits of RI are given in Table II. Without the knowledge of system voltage distortion, E_n has been assigned the worst case value given in (3).

Table II can be interpreted as follows: if the system resonates at both 5-th and 7-th harmonics with the same RI_n ratio, the index limit is 38.89; if it resonates at the 7-th and 11-th harmonics, the index limit is 42.21; and so on. It can be seen that the higher the harmonic order, the larger the index limit. The difference between the index limits is insignificant however. Therefore, to simplify the proposed guideline, a conservative index limit that corresponds to the 5-th and 7-th harmonic case can be selected as the limit representative of the two-harmonic case in general.

If three harmonics are included, every combination of three harmonics should be calculated. Similar to the case of two harmonics, however, the most conservative case that corresponds to the combination of the 5-th, 7-th, and 11-th harmonics, is used to establish a general limit for the three-harmonic case. The index limit RI was found to be 30.74 in this case. For the case of four harmonics, the limit RI was found to be 26.11.

C. Case of Different Harmonic Voltage Distortion Levels

In Sections III-A and III-B, the most conservative results were obtained by considering the worst background voltage distortion (i.e., the distortion is equal to the limit set by the IEEE Standard 519). Higher voltage distortion can cause larger capacitor harmonic current, and therefore, lower index limits, while lower voltage distortion will contribute to lower harmonic current, and hence, allow higher harmonic resonance index limits.

By varying the background voltage distortion level, a set of limit values for RI can be determined. The results are a harmonic resonance chart shown in Fig. 4. When deriving this chart, we have assumed that all harmonics have the same value of α. Each curve represents the worst combination of the background harmonics.

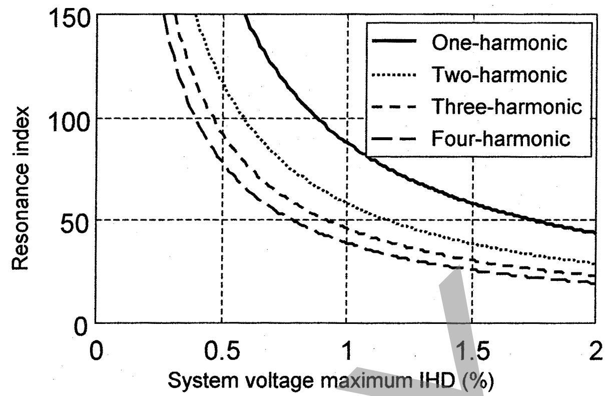

Fig. 4. Guideline chart of harmonic resonance index.

Fig. 4 is the complete harmonic resonance guideline chart for shunt capacitor applications at the voltage level 69∼138 kV. The larger the number of harmonics included, the lower the index limit. A higher background voltage distortion also results in a lower index limit.

IV. APPLICATION EXAMPLES

The guideline in Fig. 4 is straightforward and quite easy to use. The assessment of the harmonic resonance problem can be summarized in the following steps:

1) Determine the system Thevenin harmonic impedance by frequency scan studies [5]–[7].
2) Calculate the system harmonic resonance indices for each harmonic order of interest.
3) Determine the system Thevenin voltage distortion and the dominating harmonic orders. If this information is not available, take the IEEE Standard limit of 1.5%.
4) Find the index limit corresponding to the system voltage distortion from the proposed guideline chart (Fig. 4).
5) Compare the system indices with the index limits and decide if there exists harmonic resonance problem.

In the following, two examples are provided to illustrate the application of the proposed harmonic resonance guideline.

A. Assessment Without Voltage Distortion Information

The system is shown in Fig. 1. The parameters are given as

Voltage level: 138 kV.

Frequency response (Fig. 5). The principal harmonic impedances are shown in Table III. The base MVA is 100 MVA.

Capacitor size to be installed: 27 MVar.

The harmonic resonance indices of this system were calculated and the principal ones are shown in Table III.

Since the system voltage distortion information is unknown, the IEEE Standard 519 limit is considered. Corresponding to $\alpha = 1.5\%$, the index limits can be found from the guideline

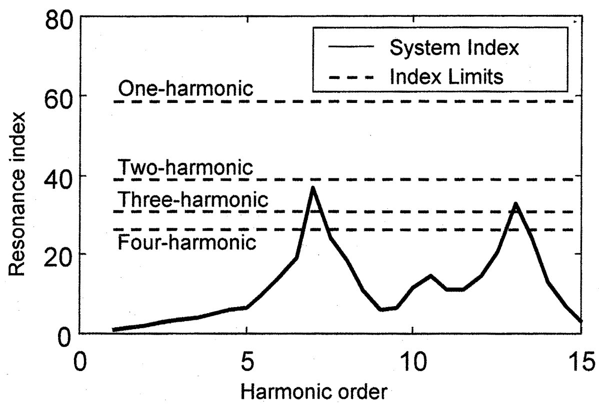

Fig. 5. Example of resonance assessment without voltage distortion information.

TABLE III
PRINCIPAL HARMONIC IMPEDANCES AND INDICES

Harmonic Order	1	5	7	11	13
System Impedance	0.038 +j0.086	0.137 +j0.224	0.061 +j0.451	0.093 +j0.653	0.110 +j0.280
Harmonic Index	1	6.77	36.54	10.98	32.86

chart in Fig. 4 as 58.4, 38.9, 30.7, and 26.1 for one-, two-, three-, and four-harmonic cases, respectively.

Fig. 5 shows the system harmonic index and the index limits. It can be concluded that

1) Any single harmonic resonance will not cause a problem since every system harmonic resonance index is less than the one-harmonic index limit.
2) Similarly, combinations of any two harmonics will not result in a resonance problem since the system harmonic indices are smaller than the two-harmonic index limit.
3) The 7-th and 13-th system harmonic indices are larger than the three-harmonic index limit. This implies that the combination of three-harmonic resonance may cause a problem.
4) If the system is rich in 7-th and/or 13-th harmonic sources, a detailed harmonic analysis is recommended.

B. Assessment With Voltage Distortion Information

Here, in addition to the system information given in Example A, the voltage distortion information as a percentage of the fundamental is also available. Fig. 6 shows two cases with different voltage harmonic components.

For case 1, the maximum voltage distortion is 1%. The chart in Fig. 4 gives the index limits as 87.6, 58.3, 46.1, and 39.2 for 1% voltage distortion. All of the system indices in Table III are less than any one of these index limits. Hence, it may be concluded that there is no need to worry about potential resonance problems. On the other hand, Fig. 6 shows that Case 1 has two dominating harmonics—7-th and 11-th, which means that it is not necessary to consider three-harmonic resonance. With this

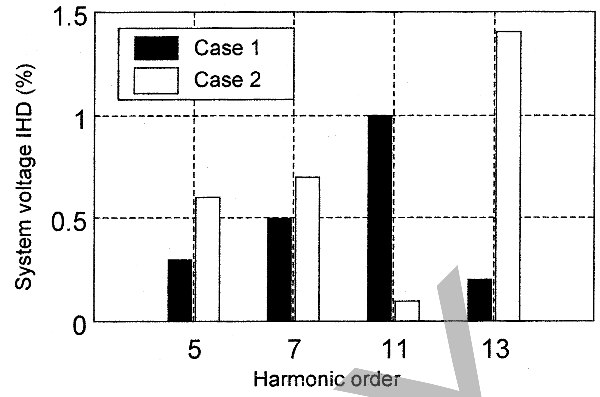

Fig. 6. System voltage distortion information.

information, we can also conclude from Fig. 5 that the capacitor installation will not cause a harmonic resonance problem, even though the detailed voltage distortion percentage is kept unknown.

For Case 2, three dominating harmonics are shown in Fig. 6, and 7-th and 13-th are among them. Taken together with conclusions (3) and (4) in Example 1, it can be inferred that there might be a resonance problem with the capacitor installation. Therefore, in this case, a detailed harmonic analysis is strongly recommended.

C. Discussions

Considering the complexity of power systems, multiple resonances may exist at the point of capacitor installation, as shown in Fig. 5. The resonant frequencies may not coincide with harmonic frequencies. To be conservative, the maximum RI between $(\mathrm{n} - 0.5, \mathrm{n} + 0.5]$ can be taken as the n-th resonance index.

It is worth pointing out that a complex power system often has quite a few operating scenarios. To be concise, only one scenario is considered in the examples. However, for each scenario, as long as the system Thevenin harmonic impedance is obtained by the frequency scan method, the proposed guideline can be applied to determine the impact of capacitor installation on harmonic resonance. Then final conclusion can be drawn after checking all of the scenarios.

Since the worst conditions were considered in formulating the proposed guideline, the analysis results could be conservative. The guideline can be further improved in the following ways.

1) A warning region can be defined to refine the harmonic index chart. For example, a warning region could be a 10% zone above the index limits in the guideline chart. In such a case, only the area above the warning region will require detailed system harmonic analysis for further investigating the system-capacitor resonance problem.
2) The system harmonic voltage E_n is an important factor for evaluating the severity of harmonic resonance. It can be determined by field measurements.
3) The capacitor ratings in (17)–(20) were considered as the operating values (i.e., the fundamental components). However, in practice, the ratings are usually larger than

the operating values to maintain a safety margin. If the real operating values are obtained, (17)–(20) can be modified by considering a coefficient "a," such as $V_{rms,rated} = aV_{C1}$.

4) To simplify the derivation, each harmonic was treated "equally" in the guideline. In other words, the index limits have been calculated from (29)–(32). However, the index limit is not necessarily the same for each harmonic. Calculating RI directly from (21)–(24) is a more accurate way to investigate the resonance problem. However, such an approach is more complicated.
5) The guideline chart is developed with capacitor damage as the main concern, which is the most common case. Other limiting factors could also be included if they become a main issue.

V. Conclusion

In this paper, a harmonic resonance index is proposed and a general guideline is presented for quick assessment of the harmonic resonance potential caused by shunt capacitor installations. The guideline gives the relationship between the index and the background voltage distortion at the capacitor bus. This relationship has been displayed in the form of a boundary curve in the "Resonance Index—Voltage Distortion" space. The region enclosed by the boundary curve represents the "Problem Region" with a strong likelihood of the installed capacitor being damaged. Detailed system harmonic analysis is recommended when the harmonic resonance index is located in this region. The region exterior to the boundary curve represents the "Safe Region" thereby allowing system planners to circumvent costly detailed harmonic studies. Examples illustrate that the application of this guideline is straightforward and how the results may be interpreted.

The chart in Fig. 4 is applicable to the voltage level 69$\sim$138 kV. Similar charts may be readily developed for other voltage levels, using the same methodology.

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