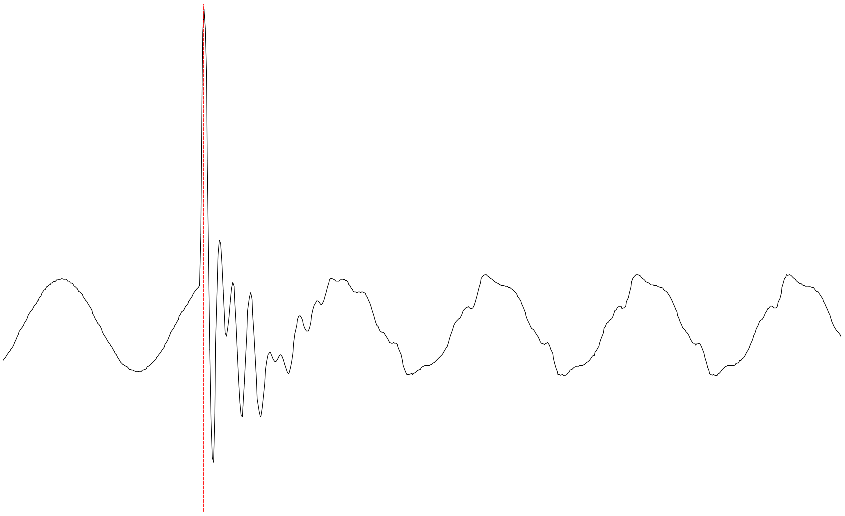
Harmonics and Transients Tech Notes



Issue # 96-3 September 1996 Editor: Karen Brown
Project Manager: Susie Brockman
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Letter from the Project Manager:

We have a busy two months ahead for our members and I encourage each of you to test the system to the limits as new support features are added to the group.

New List Server for PATH Members Only

A new list server has been established for PATH Members Only. If you would like join the group please send an e-mail to path-request@list.electrotek.com with the word SUBSCRIBE in the message body (not the subject or title). You will automatically be added to the mailing list and will receive any and all messages sent to the group. You can also send messages to the entire group with just one e-mail. If you want to get off of the list, once you are on, just send an e-mail with UNSUBSCRIBE in the body and we will remove you from the list. Many of you probably already subscribe to the power globe list and are familiar with how this works. It can be very beneficial for exchanging information.

Web Site

The PATH web site has been on-line for about a month now. I hope that you have logged on to the site. The site is located at http://www.pqnet.electrotek.com/pathmemb/path.htm. To get into the files you will need a user id and password which has been assigned by Electrotek.

PATH Users Group Meeting and Workshop

There is only one seat left. If you are planning to come. Please call me as soon as possible.

We would like your feedback on the services that are being offered for the group. If you are having problems accessing the information, please let us know so we can work to make your membership beneficial.

If you have any questions regarding your membership, please give me a call at (423) 470-9222 ext. 141

Sincerely,

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The following article presents a method whereby computations done in the programs of PSPICE and Micro-Cap are made more efficient. Even though Electrotek does not support either of these programs, this article is presented as a source of information for anyone currently using or having an interest in them.

Increase of Accuracy and Rate of Computer Aided Calculations of Transient Processes

The existing simulation programs (for example PSPICE, or Micro-Cap) furnish an excellent service(maintenance) for the user. But when some kinds of transient processes are computerized, for example in band-pass networks of high quality, these programs appear to be inefficient and sometimes even unfit for practical use. This subject, in particular, was addressed in the paper, “The Simulation Errors Introduced by SPICE Transient Analysis” [1]. This inefficiency is caused by insufficient accuracy in calculation of each time step, as the calculation in the second approximation (trapezoidal method and its modifications) is usually applied. The Runge-Kutt method permits an increase in accuracy (particularly to the fourth order) but it is seldom used because of the complexity of computations.

Taylor - series expansion of transient functions at each time step gives obvious advantages because the addition of one term of the expansion is usually more efficient than the division of a time step into a large number of parts. But to realize these advantages, the simple method of the Taylor Series expansion of transient functions is needed. The principle solution of this problem was found by Professor A.D. Artym in the 1980’s. After that he and his colleagues developed the practical forms of these solution applications and performed their approbations for practical problems. The importance of the suggested ideas has been confirmed in 1994.

In essence, a new algorithm of computational process is proposed. Instead of discretes of transient function, the coefficients of Taylor series expansion in matrix form are calculated. This permits the user to find the value of the function for any instant of time within the given time step, which may be essentially larger than the usual time step in commonly used programs. In some cases, the transient process in the whole given time interval may be taken as one such “step”.

The developed algorithm may be applied for commonly used programs (PSPICE, Micro-Cap and others) while keeping all the service and characteristics of these programs. In this case the rate and (or) the accuracy of computation essentially increases. The use of this algorithm appears to solve the problems practically unable to be solved earlier. A good example is the process calculation in circuits consisting of lumped elements (R, L, C) and of feeders.

In order to illustrate the advantages of the developed method, the RLC - resonant circuit, simulated in [I], was taken. When choosing the quality of this circuit Q=100, time step h=0.IT_0 (10 points in period T_0) and calculating the process up to the moment t equal to 100 of periods T_0 our method provides a ten-fold gain in both accuracy and process computation rate in comparison with the Micro-Cap 3 simulation program. Our method when choosing an optimum step h = 25 T_0 enables us to calculate the process up to t=100 T_0, quicker by a factor of 60 than the Micro-Cap 3 program does, while maintaining a 10 fold gain in accuracy.

Transients processed in 10th order band-pass Batterworth filter gives the more convincing proof of the advantages of our method. The output voltage $U_2 = U_{c5}$ has been calculated when the voltage $U_1(t) = 2\cos\Omega t$ was fed to the input of the filter with normalized parameters (Fig 1). In order to find the reference analytical solution, the Laplace transfer function of the fifth-order low-pass filter was used. Its roots, i.e. the solutions of its characteristic equation are known, so this function may be represented as a sum of five first order fractions. Applying the transformation

$$P \to P + \frac{\Omega^2}{P}$$

the low-pass filter is transformed to 10th order band-pass filter. At the same time each of the simple fractions is transformed to the fraction of the second order, which may be represented as two fractions of the first order. Combining the pairs of complex conjugate fractions of the first order we obtain five real fraction of the second order and applying to them the reverse Laplace transformation we obtain:

$$U_{C5}(t) = \cos\Omega t - (1 + a)e^{-0.5t}\left[\cos\sqrt{\Omega^2 -)0.25}\,t - \frac{\sin\sqrt{\Omega^2 - 0.25}\,t}{2\sqrt{\Omega^2 - 0.25}}\right] +$$

$$e^{-\ {}_1 t}\left(U_{1C}\cos\Omega_1 t + U_{15}\sin\Omega_1 t\right) + e^{-a_2 t}\left(U_{2C}\cos\Omega_2 t + U_{2S}\sin\Omega_2 t\right) +$$

$$e^{-a_3 t}\left(U_{3C}\cos\Omega_3 t + U_{3S}\sin\Omega_3 t\right) + e^{-a_4 t}\left(U_{4C}\cos\Omega_4 t + U_{4S}\sin\Omega_4 t\right)$$

Where:

$$a_1 = \frac{1}{2}\sin\frac{p}{10} + B_1; \qquad \Omega_1 = \frac{1}{2}\cos\frac{p}{10} + A_1;$$

$$a_2 = \frac{1}{2}\sin\frac{p}{10} - B_1; \qquad \Omega_2 = \frac{1}{2}\cos\frac{p}{10} + A_1;$$

$$a_3 = \frac{1}{2}\sin\frac{3p}{10} + B_2; \qquad \Omega_3 = \frac{1}{2}\cos\frac{3p}{10} + A_2;$$

$$a_4 = \frac{1}{2}\sin\frac{3p}{10} - B_2; \qquad \Omega_4 = \frac{1}{2}\cos\frac{3p}{10} + A_2;$$

$$U_{1C} = \frac{a}{2}\left[1 + \frac{A_1\cos\frac{p}{10} + B_1\sin\frac{p}{10}}{2\left(A_1^2 + B_1^2\right)}\right];$$

$$U_{1S} = \frac{a\left(-A_1\sin\frac{p}{10} + B_1\cos\frac{p}{10}\right)}{4\left(A_1^2 + B_1^2\right)};$$

$$U_{2C} = \frac{a}{2}\left[1 - \frac{A_1\cos\frac{p}{10} + B_1\sin\frac{p}{10}}{2\left(A_1^2 + B_1^2\right)}\right] = a - U_{1C};$$

$$U_{2S} = \frac{a\left(-A_1\sin\frac{p}{10} + B_1\cos\frac{p}{10}\right)}{4\left(A_1^2 + B_1^2\right)} = U_{1S};$$

$$U_{3C} = \frac{b\left(-A_2 \sin\frac{3p}{10} + B_2 \cos\frac{3p}{10}\right)}{4\left(A_2^2 + B_2^2\right)};$$

$$U_{3S} = -\frac{b}{2}\left[1 + \frac{A_2 \cos\frac{3p}{10} + B_2 \sin\frac{3p}{10}}{2\left(A_2^2 + B_2^2\right)}\right];$$

$$U_{4C} = \frac{b(A_2 \sin\frac{3p}{10} - B_2 \sin\frac{3p}{10}}{2(A_2^2 + B_2^2)} - U_{3C};$$

$$U_{4S} = \frac{b}{2}\left[1 - \frac{A_2 \cos\frac{3p}{10} + B_2 \sin\frac{3p}{10}}{2\left(A_2^2 + B_2^2\right)}\right];$$

$$A_1 = \sqrt{\frac{4\Omega^2 + \cos\frac{p}{5} + \sqrt{16\Omega^4 + 8\cos\frac{p}{5} + 1}}{8}}; \quad B_1 = \frac{\sin\frac{p}{5}}{8A_1};$$

$$A_2 = \sqrt{\frac{4\Omega^2 - \sin\frac{p}{10} + \sqrt{16\Omega^4 - 8\sin\frac{p}{10} + 1}}{8}}; \quad B_2 = \frac{\cos\frac{p}{10}}{8A_2};$$

$$a = \frac{1}{\sin\frac{p}{10} + \sin\frac{3p}{10}}; \qquad b = \frac{1}{\cos\frac{p}{10} - \cos\frac{3p}{10}}.$$

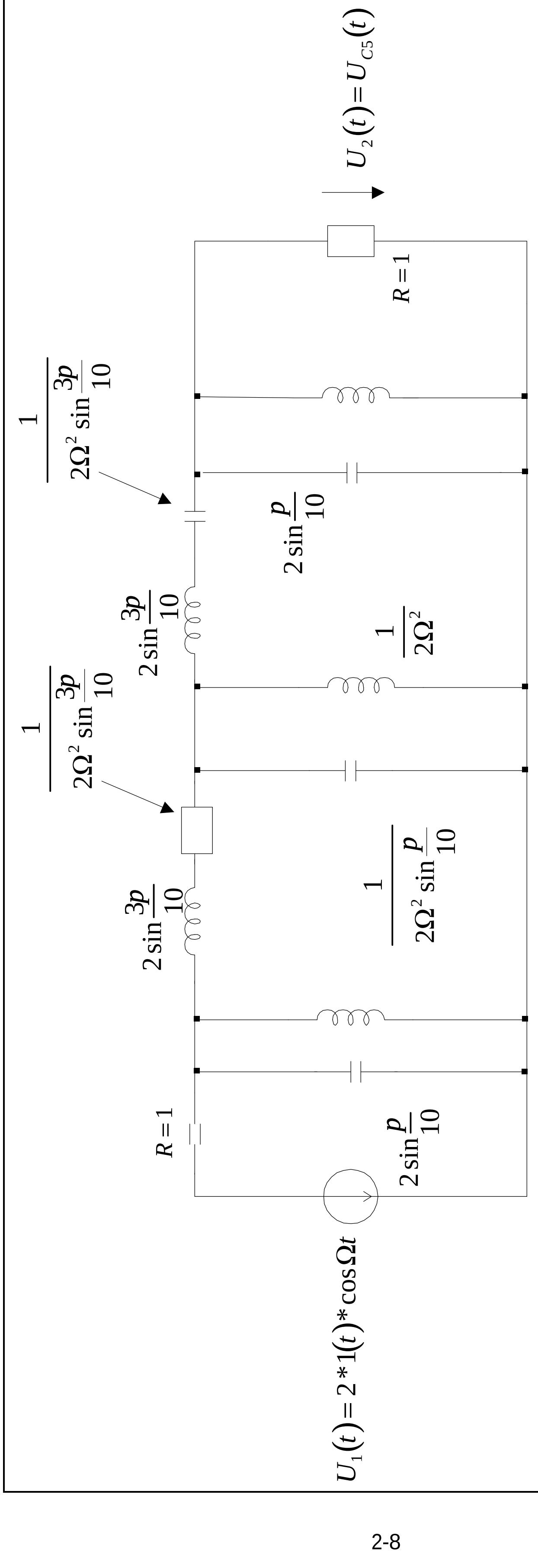
$U_2(t) = U_{C5}(t)$
$R = 1$
$\frac{1}{2\Omega^2 \sin\frac{3p}{10}}$
$2\sin\frac{p}{10}$
$2\sin\frac{3p}{10}$
$\frac{1}{2\Omega^2}$
$\frac{1}{2\Omega^2 \sin\frac{3p}{10}}$
$2\sin\frac{3p}{10}$
$\frac{1}{2\Omega^2 \sin\frac{p}{10}}$
$R = 1$
$2\sin\frac{p}{10}$
$U_1(t) = 2*1(t)*\cos\Omega t$

Figure 1

The step-like cosine voltage with normalized frequency Ω and doubled unit amplitude is fed to an input of the filter with normalized parameters (Fig 1). The calculation is performed up to the moment t=1500 $2p / \Omega = 1500T_0$ when the envelope fluctuations decrease to sufficiently low value (Fig. 2). The relative error of numerical solutions has been estimated by the formula:

$$\sum \left| \frac{U_C - U_{Canal}}{U_{Canal}} \right| * 100\%$$

where U_C is the numerical solution for the filter voltage for the given moment obtained either by the Micro-Cap 3 simulation program or by our method, is the analytical solution for the filter voltage at the same moment.

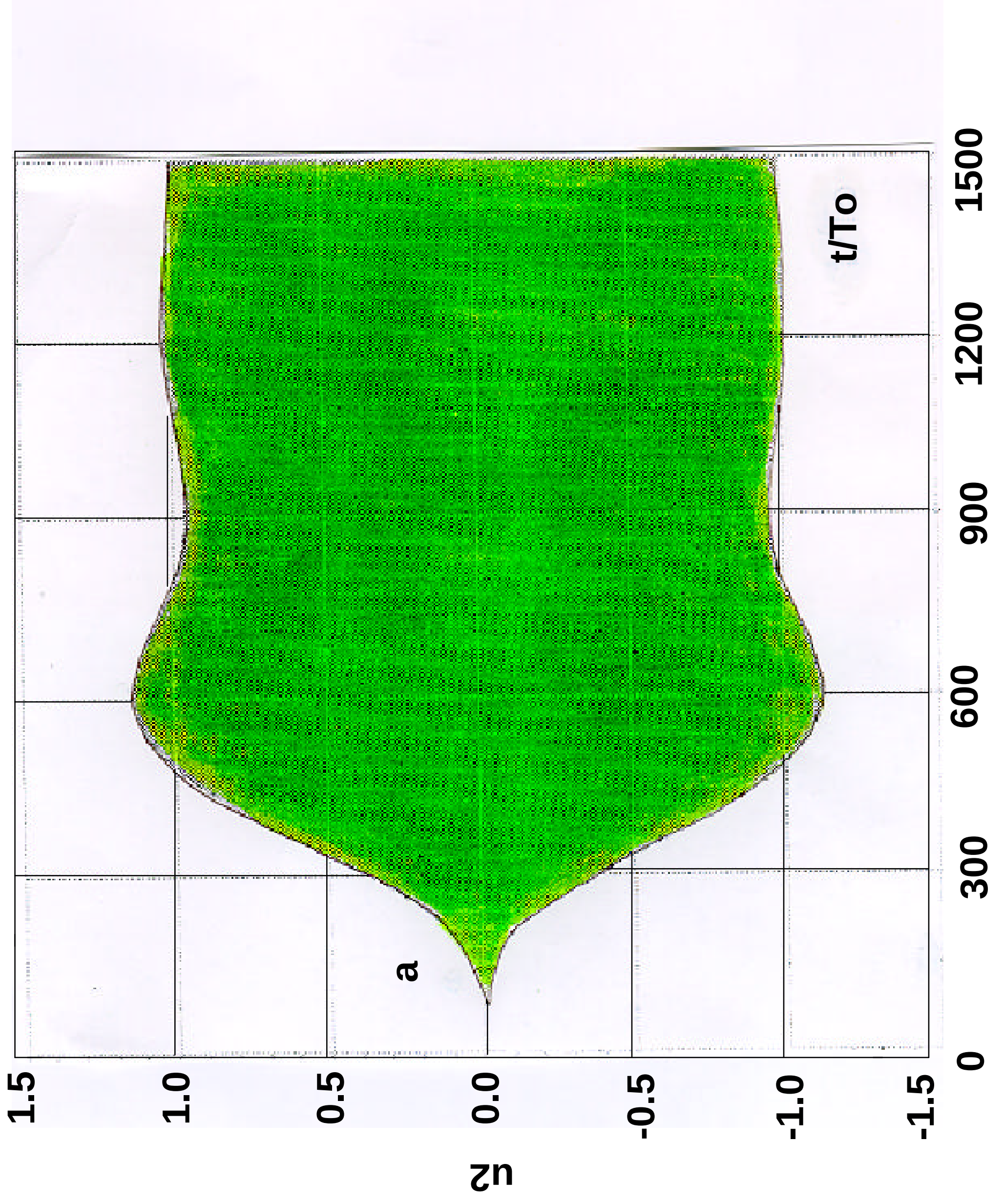

Figure 2

The simulation of the transient processes by the Micro-Cap 3 program with IBM 486-dx computer in the filter studied gives the following results. The provision of the given relative error $e = 0.1\%$ for the calculation of the first check point of the voltage $U_{C5} = U_2$ for $t = 50T_0$ required 55 seconds of computer time. The second check voltage U_{C5} for $t = 100T_0$ has been calculated only with the relative error $e = 0.42\%$ (under the program controlling parameters close to limiting permissible) during the computer time equal to 27 minutes. The extension of the calculation by Micro-Cap 3 up to the third check value of the voltage for $t = 150T_0$ (maintaining the same program controlling parameters) resulted in the growth of relative error up to $e = 3.8\%$ and required 50 minutes of computer time. Thus, the acceptable accuracy ($e = 3.8\%$) of the coincidence with the standard function is achieved only for the first 150 periods of carrier frequency, i.e. at 1/10 portion of the design interval (line a in Fig. 2). Practically the calculation of the process by the Micro-Cap 3 program solely with the error acceptable for practice is quite impossible even for the interval $t = 300T_0$ constituting only 20% from the given one (1500 T_0).

While using our method, the calculation of the whole process (Fig. 2) up to the moment $t = 1500T_0$ with relative error $e \le 0.01\%$ for the step $h = 0.1T_0$ and the number of Taylor series $q = 9 + 12$ has been performed during 55 seconds.

For the optimum step $h = 3T_0$, $e \le 0.01\%$ and the term number of Taylor series $q = 57 - 59$ the minimum time for the calculations of the whole process was ~ 9 seconds. The ability of our method to operate with optimum step $h=3T_0$ offers the possibility of very fast calculation of the envelope of high-frequency process. The method enables us to turn to small step (for example $h = 0.1T_0$) if the detailed calculation in some part of the process is necessary, and to accomplish such a calculation (Fig. 3).

The results presented demonstrate especially large advantages and possibilities of the method proposed for the solution of computer simulation problems and for the analysis of transient processes in complicated electrical networks of high quality or stiff processes, without changing the algorithm.

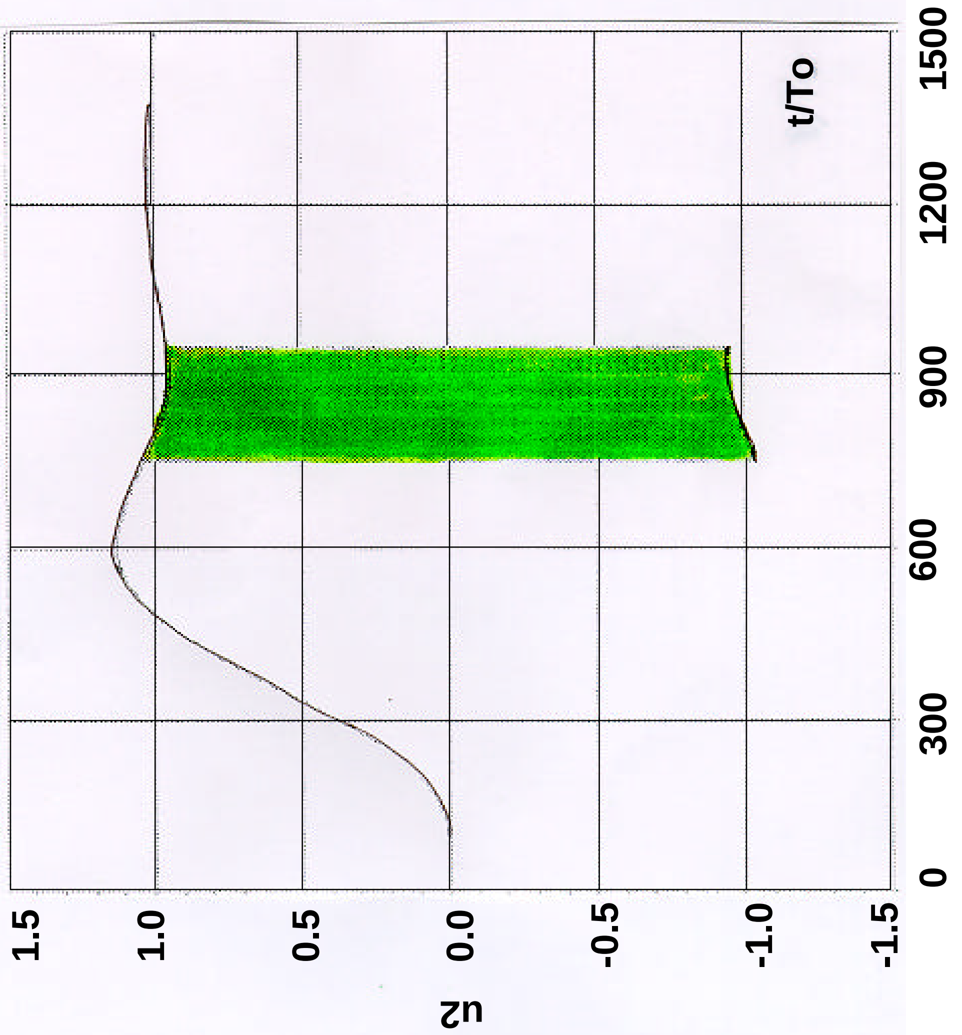

Figure 3

Reference

[1] A. Brambilla, D. D'Amere. "The Simulation Errors Introduced by the SPICE Transient Analysis." IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, January 1993, Vol. 40, pg. 57.

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Calculation of the Maximum Anticipated Per-Unit Transient Switching Overvoltages on the Craig-Rifle 345V Transmission Line

Purpose

The purpose of the study is to calculate the maximum anticipated per-unit switching transient overvoltages on the Craig-Rifle 345kV transmission line. This is to determine the minimum approach distance for ac live-line maintenance work.

Introduction

The study is performed at the request of the Transmission Lines Department of the Public Service Company of Colorado in response to the new minimum safe working clearances published by OSHA and NESC. The clearances published in these standards are computed using a maximum anticipated transient overvoltage of 3.0 per unit. Reduced working clearances based on maximum transient overvoltages which are less than 3.0 p.u. can only be applied after transient overvoltages have been determined by engineering analysis. The required minimum phase-to-ground clearance is 73 inches at 5300 feet to 81 inches at the maximum 8700 feet and are based on maximum per unit switiching overvoltage of 2.2 calculated from an EMTP study. The Public Service Company of Colorado's (PSCo) Manual of Safe Practices requires a minimum of 7 feet (84 inches) working clearance at 345kV.

Scope of the Study

The objective of the EMTP study is to examine the maximum switching surges which the Craig-Rifle transmission line may be subjected to during live-line maintenance. To do this, the following cases are run and assumptions made to determine the maximum transient overvoltages on the Craig-Rifle line for live-line maintenance.

1. Transient overvoltages due to:
    a. energization
    b. reclosing of adjacent lines which terminate into Craig and Rifle 345kV buses.

These study conditions should give the maximum switching surges possible on the Craig-Rifle line during live-line work.

Also considered, but understood as not directly applicable to live-line work, are the following additional cases:

2. Transient overvoltages due to energization of the line by closing one terminal breaker of the line. This is not an actual operating condition during live-line maintenance work, but it is considered as an informational/conservative case for switching surge.

3. Transient overvoltages due to high speed reclosing (.5 seconds or less) into trapped charge on the Craig-Rifle line after a single-line-to-ground fault. This is also not an actual operating condition (reclosing will be blocked), but this condition should yield the maximum switching surge conditions possible on this line under normal operating conditions (however, not during live-line maintenance work).

Model Development

A 3-phase model is developed with the system equivalent sources at the Ault and Grand Junction 345kV buses for the first case (see Fig. 1), and another model is developed with equivalent sources at Craig and Rifle for the last two cases. Induced voltages due to mutual coupling of the lines parallel to the 345kV lines are not included in the model for simplification. This simplification gives higher and more conservative results and is considered acceptable based upon the results of studies done by WAPA for Tri-State on the same system area. EMTP model fault currents are compared with the fault study from the Aspen (One-Liner fault study program) to check the validity of the model. The transmission lines are modeled using the J. Marti model and the distributed parameter line mode. The results of the two models using IVI or VVV insulator strings (line insulator/tower configuration) are comparable and very close. Most of the cases are run with J. Marti model using IVI strings. Systematic switches are used to simulate closes at multiple points on the voltage waveform. Arresters at each end of the Craig-Rifle line are modeled. The 82 mile Craig-Rifle line is segmented into eight approximately eleven mile lengths to determine the voltage profile along the line.

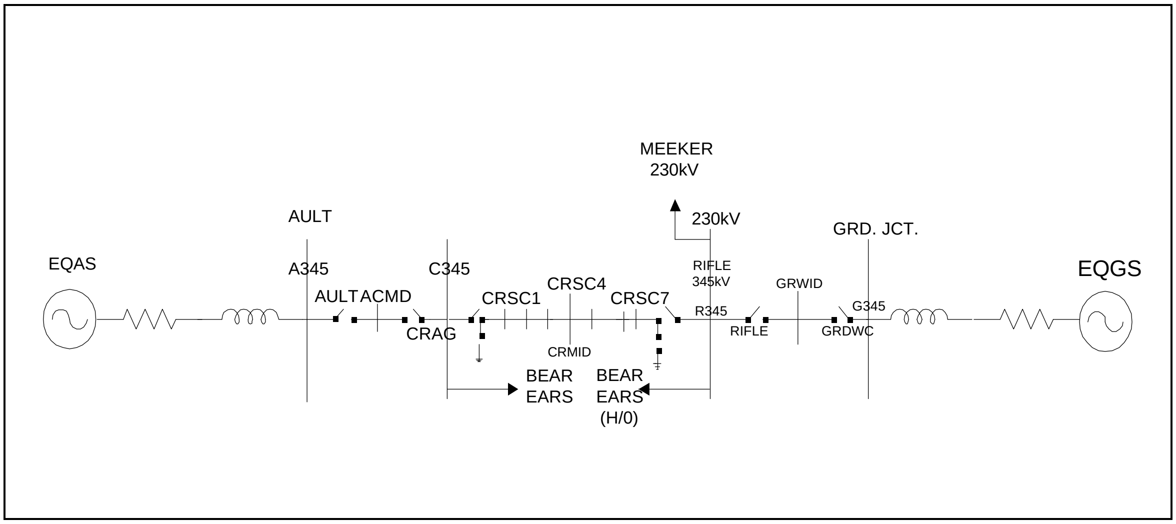

Figure 1: Craig-Rifle 345kV Line

Since standard practice is to address only switching surges for 345kV application, surges due to lightning are not considered as a part of this study. However, PSCo Transmission Lines Department raised concerns/questions regarding lightning surge which may occur somewhere along the line which is out of sight due to the mountainous region in which the Craig-Rifle line is located. PSCo is in the process of investigating possible lightning surge working clearance requirements for this line. The assumption is made that the live-line maintenance will not be performed during bad weather. Phase-to-phase clearance for live-line maintenance is not considered as a part of this study, as the distances between two phases at the towers varies from 25 to 36 feet. These distances are far in excess of the phase-phase values listed in OSHA Table R-8 (e.g. 12 feet 6 inches at 3300 feet, or 14 feet 6 inches at 8700 feet altitude)[1].

Table R-8: AC Live Line Work Minimum Approach Distance with Overvoltage Factor Phase-To-Phase Exposure [1]

Max. anticipated per unit Trans. Overvolt.	Distance in feet-inches						
	Maximum phase-to-phase voltage in kilovolts						
	121	145	169	242	362	552	800
1.5	....	....	....	....	....	7-4	12-1
1.6	....	....	....	....	....	8-9	14-6
1.7	....	....	....	....	....	10-2	17-2
1.8	....	....	....	....	....	11-7	19-11
1.9	....	....	....	....	....	13-2	22-11
2.0	3-7	4-1	4-8	6-1	8-7	14-10	26-0
2.1	3-7	4-2	4-9	6-3	8-10	15-7	....
2.2	3-8	4-3	4-10	6-4	9-2	16-4	....
2.3	3-9	4-4	4-11	6-6	9-6	17-2	....
2.4	3-10	4-5	5-0	6-7	9-11	18-1	....
2.5	3-11	4-6	5-2	6-9	10-4	....	....
2.6	4-0	4-7	5-3	6-11	10-9	....	....
2.7	4-1	4-8	5-4	7-0	11-2	....	....
2.8	4-1	4-9	5-5	7-2	11-7	....	....
2.9	4-2	4-10	5-6	7-4	12-1	....	....
3.0	4-3	4-11	5-8	7-6	12-6	....	....

Note: the distance specified in this table may be applied only where the maximum anticipated per-unit transient overvoltage has been determined by engineering analysis and has been supplied by the employer. Table R-6 applies otherwise.

Results

As a result of PSCo's studies, the maximum expected per unit switching surge voltage which could occur anywhere on the Craig-Rifle 345kV line is 1.91 p.u. (without any added margin). In consideration of ANSI standards practices, and to be conservative, we add a 15% safety margin to the calculated maximum expected switching surge. This results in 2.2 p.u. switching surge for a phase-to-ground clearance of 6 feet 9 inches (81 inches) at 8700 feet elevation. When compared to the actual minimum phase-to-ground clearance of 8 feet 3 inches for V insulator string and 11 feet 3 inches for I string at the transmission line's structure type TSB, this corresponds to a margin of 22.2% and 66.6% ((i.e. Actual clearance @ the tower/Minimum clearance -1) X 100).

Table 1 gives the recommended minimum clearance for maintenance work to be done at different altitudes along the Craig-Rifle 345kV line for switching surge of 2.2 p.u. The minimum working clearance shown in Table I is calculated based on OSHA Table R-7.

Table 1*

Recommended minimum working clearances per OSHA, Table R-7 phase-to-ground based upon EMTP studies of Craig-Rifle at 2.2 p.u. switching surge with a conservative safety margin of 15% @345kV.

Altitude (feet)	Correction Factor	Min PH-GND Clearances (inches)
3000	1.00	69.00
3300	1.00	69.00
4000	1.02	70.45
5000	1..05	72.52
5500	1.07	73.55
6000	1.08	74.59
6500	1.10	75.62
7000	1.11	76.66
7500	1.13	77.69
8000	1.14	78.73
8500	1.16	79.76
9000	1.17	80.80
9500	1.19	81.83
10000	1.20	82.87
10500	1.22	83.90
11000	1.23	84.94
11500	1.25	85.97
12000	1.26	87.01

*Note: l. The altitude of Crag-Rifle 345kV line varies from 5300-8700 feet.
2. Minimum Ph-Gnd Conductor-Tower actual clearance is 8 feet 3 inches for V and 11 feet 3 inches for I string insulator.

Table R-7: AC Live-Line Work Minimum Approach Distance with Overvoltage Factor Phase-To-Ground Exposure

Max. anticipated per-unit overvolt.	Distance in feet-inches						
	Maximum phase-to-phase						
	121	145	169	242	362	552	800
1.5	....	....	....	....	....		
1.6	....	....	....	....	....		
1.7	....	....	....	....	....		
1.8	....	....	....	....	....		
1.9	....	....	....	....	....		
2.0	2-5	2-9	3-0	3-10	5-3		
2.1	2-6	2-10	3-2	4-0	5-5		
2.2	2-7	2-11	3-3	4-1	5-9		
2.3	2-8	3-0	3-4	4-3	6-1		
2.4	2-9	3-1	3-5	4-5	6-4		
2.5	2-9	3-2	3-6	4-6	6-8		
2.6	2-10	3-3	3-8	4-8	7-1	....	....
2.7	2-11	3-4	3-9	4-10	7-5	....	....
2.8	3-0	3-5	3-10	4-11	7-9	....	....
2.9	3-1	3-6	3-11	5-1	8-2	....	....
3.0	3-2	3-7	4-0	5-3	8-6	....	....

References:

[1] Federal Register. Vol. 59, No. 20. Monday, January 31, 1994. Rules and Regulations. Pages 4445-4446.

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Harmonic Analysis and Filter Design for Ski Resort Systems

This article discusses harmonic analysis and filter design for systems serving ski resorts. The 12.47 kV system of Figure 1, which serves about 6000 HP of 480 V, six-pulse DC adjustable speed drives (ASDs) will be our example.

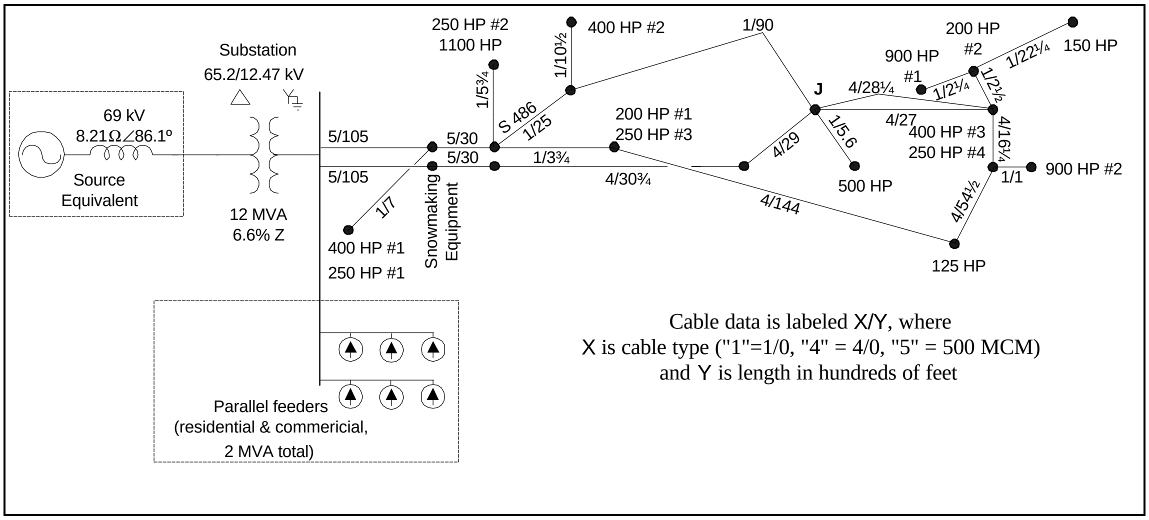


Figure 1: Simplified system diagram

Using Measurements to Construct Harmonic Source Models

There is no practical means of measuring current on the 12.47 kV distribution system shown on Figure 1. Metering CTs are not installed on the feeders, and the clamp-on CTs provided with the harmonic monitor which was used for the measurements are rated for 600 V_{RMS} maximum.

Measurements can be taken at the individual 480 V ASDs, but then the diversity among these harmonic sources must be estimated when calculating IEEE 519 compliance. First, there is load diversity - the ASDs will not all be at peak load simultaneously. Second, there is phase angle diversity, which can be explained as follows: if two harmonic sources each inject 1 A at a certain harmonic, the total current flowing into the system will not be 2 A, but something less, because the phase angles of the injected currents are not the same. One method for estimating diversity in this type of situation is:

- For load diversity, measure each ASD at frequent intervals during the peak load period, and set the harmonic current magnitudes in the corresponding SuperHarm *â* NonlinearLoad model to the average of the samples.
- For phase angle diversity, select a measurement for each ASD whose fundamental current was close to the average computed above. Set the harmonic current phase angles in the corresponding SuperHarm NonlinearLoad model to the phase angles from that measurement.

Use NonlinearLoad rather than ISource. Most monitors reference harmonic phase angles to the fundamental voltage, and NonlinearLoad is based on this assumption. SuperHarm *â* automatically calculates the phase angle of the fundamental voltage at each NonlinearLoad, then adjusts the phase angles of the harmonic currents accordingly. However, in order to use the NonlinearLoad model, you must know the fundamental voltage magnitude and displacement power factor at the instant the harmonic current spectrum was recorded. Be aware that there are some monitors that record voltage and current spectra simultaneously, yet cannot provide this data.

Modeling the System in SuperHarm *â*

As most of the load is balanced three-phase, the system was modeled using a single-phase positive sequence equivalent. Including cable charging capacitance in the model was very important, as the system has over 20 miles of underground cable. Figure 2 shows that the charging capacitance is large enough to produce a parallel resonance at the 16th harmonic.

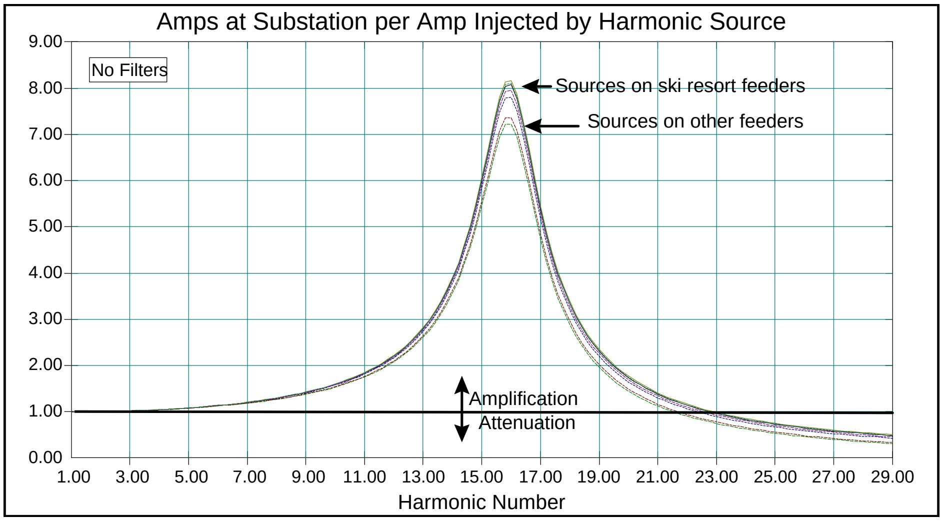


Figure 2: Current amplification scan of system without filters

Before moving on, I should point out that Figure 2 is not quite the same as the harmonic impedance plots often seen in Tech Notes. A harmonic impedance plot is produced by applying a 1 A variable frequency current source at some point in the system, and then plotting the voltage at that point. The Y axis can be labeled "impedance" since Z(h) = V(h) when I(h) = 1.

Instead of system voltage, Figure 2 plots current into the substation. It has the same shape as an impedance plot - both show that parallel resonance occurs at the 16th harmonic. However, the Y axis values on the amplification plot are more helpful in visualizing the severity of the resonance: observe that at the 16th harmonic, 8 A will flow into the substation for very 1 A injected by harmonic loads on the system.

Evaluating IEEE 519 Compliance

There are two problems with applying the IEEE 519 harmonic current limits at a ski resort. The first is that, if the ski lift transformers are interspersed along the feeders with other customers not related to the ski resort, the point of common coupling (PCC) is not clearly definable. (Harmonic current limits should not be applied at the individual ski lift transformers, even though each has its own meter. It is not the intent of IEEE 519 that limits be placed on individual loads.)

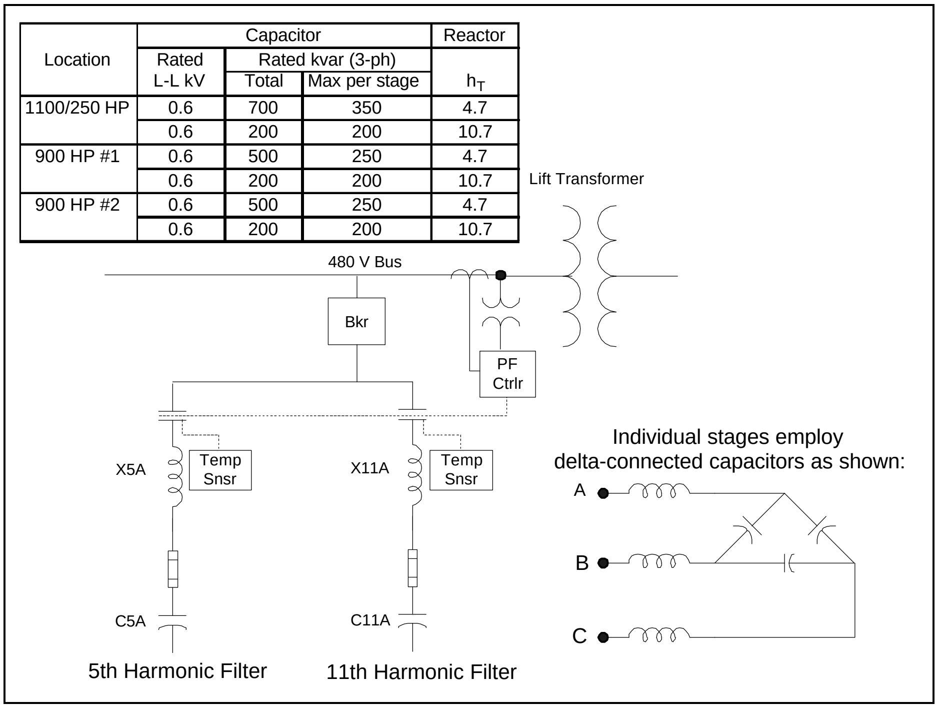
The second problem is that the IEEE 519 definition of demand current as the most recent 12 month average of the peak monthly demands is too restrictive. Including the long off season in the average would result in a very low demand current. Since harmonic current limits are given as percentages of the demand current, a low demand current means that allowable harmonic injection is also low. Therefore, the rules for applying IEEE 519 at a ski resort will require some negotiation between all parties involved in the study. This should be done before filtering is considered.

As shown in Figure 1, the ski resort is served by two feeders. The load on these feeders associated with customers not related to the ski resort is relatively small. Therefore, the PCC was drawn to include the total current in the two feeders. (In the SuperHarm model, the feeder currents were summed by inserting a very low impedance branch between the substation 12.47 kV bus and the junction of the two feeders.) It was agreed that the demand current would be based on the average monthly demand current from December through February, rather than the entire year.

The estimated harmonic current injection at the PCC is shown in Table 1. Without filters, the IEEE 519 current limits are exceeded at the fifth harmonic, and also at the 17th, due to the system parallel resonance.

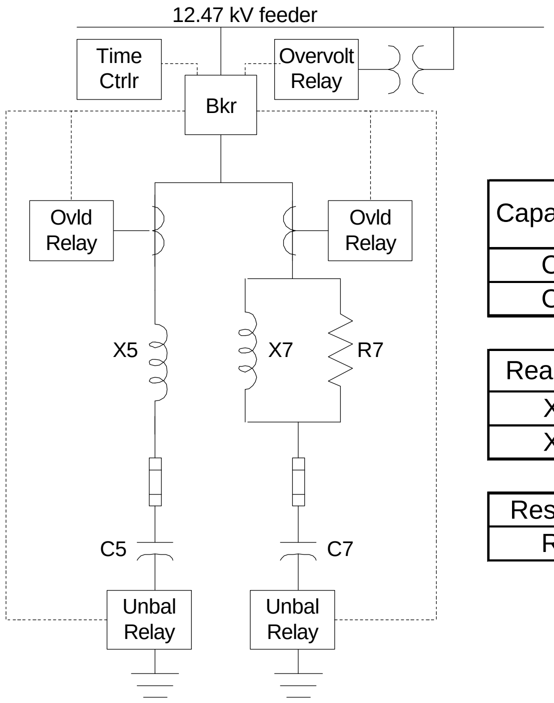
Filter Options Considered

Two mitigation schemes were considered in this study: a filter on the 12.47 kV distribution system vs. 480 V filters applied at the three lift transformers with the largest harmonic load. Component ratings for the two options are shown in Figures 3 and 4.



Location	Capacitor			Reactor
	Rated L-L kV	Rated kvar (3-ph)		
		Total	Max per stage	h_T
1100/250 HP	0.6	700	350	4.7
	0.6	200	200	10.7
900 HP #1	0.6	500	250	4.7
	0.6	200	200	10.7
900 HP #2	0.6	500	250	4.7
	0.6	200	200	10.7

Figure 3: Component values for proposed lift filters



Capacitors	Rated L-N kV	Rated kvar per phase
C5	9.96	900
C7	9.96	400

Reactors	h_T	Ω	mH
X5	4.7	4.990	13.236
X7	-	6.889	18.274

Resistor	Ω
R7	30.0

Figure 4: Component values for proposed distribution filter

Filter Design Criteria

The primary objective of applying harmonic filters is to achieve compliance with IEEE 519. Other filter design objectives are discussed below:

Minimize Voltage Rise on the System

Voltage rise at the ends of long underground feeders is a concern during periods of light system load. Harmonic filters will exacerbate this problem by adding capacitive kvar to the system.

We minimize filter delivered kvar for either option by using overrated capacitors. 600 V_{LL} capacitors are selected for the lift filters, reducing the delivered kvar to $(480/600)^2$ = 64% of the capacitor rated kvar. The distribution filters use capacitors rated at 9.96 kV_{LN}. At 7.2 kV_{LN} nominal system voltage, the filters deliver only 56% of their rated kvar. (Overrated capacitors would be required anyway, at least for the fifth harmonic filters, to keep capacitor RMS voltage duty less than 110% of the capacitor rated kV.)

The kvar delivered by the distribution filters produce a 60 Hz voltage rise at the 12.47 kV connection point of 1.9%. After adding 6% to account for normal variations in utility service voltage, we see that normal utility voltage variations should never cause system voltage to exceed the 10%-over-nominal limit normally specified in equipment standards. (Note: utility voltage variations were less than 3% over nominal during the seven days of harmonic monitoring conducted for this study.)

Even so, to be conservative, an overvoltage relay was recommended for the distribution filters. The relay would trip the filters if fundamental voltage exceeds 105% of nominal, and re-energize the filter when voltage decreases to 100% of nominal.

Concern for overvoltage is greater with the lift filters, as their delivered kvar range from 30% to 45% of the lift transformer capacities. The usual means of limiting voltage rise caused by a low voltage filter is to switch the filter on and off in response to changes in the power factor of the load current of the transformer serving the filter bus. This scheme works well, but adds about 50% to the cost of the filter.

(Note: the penalties imposed by the utility for poor customer power factor were very low in this case. Otherwise, the filter capacitors could not derated so freely. This is particularly true when the harmonic load consists of DC drives, which often have very poor displacement power factors.)

Minimize Change in Steady-State Voltage Due to Filter Switching

A filter should be sized so that switching it on or off does not cause steady-state voltage to change by more than 2% - 3%. This is not a problem for the distribution filters - the fifth harmonic filter and the high-pass filter can be switched simultaneously.

With automatic power factor control of the lift filters, the fifth harmonic and 11th harmonic filters are not switched simultaneously, but this is not sufficient. The fifth harmonic filters must be divided into a least two parallel cells, as shown in Figure 3.

Reduce Harmonic Voltage Distortion at the Lift 480 V Buses

IEEE 519-1992 recommends that the total harmonic distortion (THD) of voltage on load buses be limited as follows:

- 10% for "dedicated" buses serving only converter load. Most of the lift transformer 480V buses fall into this category.

- 8% for "general" buses serving a mix of linear and converter loads This category applies to the 480 V bus serving the 1100 HP lift and 250 HP lift #2, as the bus also serves a ski lodge.

Figures 5 shows peak VTHD trended every five minutes for the buses serving the 1100 lift/250 HP lift #2 and the 900 HP lift #1. The values greatly exceed the IEEE 519 recommended limits - 12.5% vs. 5% for the 1100/250 HP lift bus, and 19.5% vs. 10% for the #1 900 HP lift bus. Peak THD for #2 900 HP lift bus is also about 19.5%. Peak THDs at the remaining lifts are all less than the recommended limit of 10%.

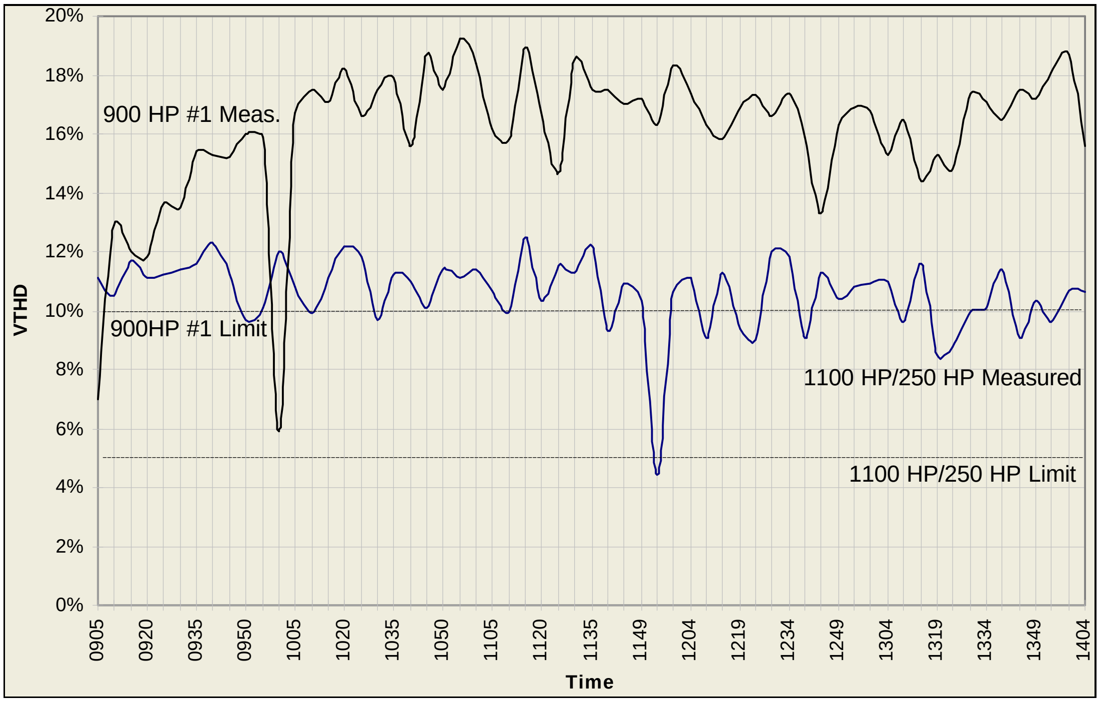


Figure 5:Peak VTHD per five minute sample interval

Even though VTHD is very high at three 480 V buses, the fact is that the lifts and other equipment served from these buses have operated without problems for 15 years. Therefore, although reducing VTHD at these buses is desirable, making compliance with IEEE 519 voltage distortion limits a filter design requirement would be a hard sell to the customer who must pay for the filters.
Reduce Overloading of Lift Transformers

Measurements at the same three 480 V buses show that peak loads exceed the rated capacity of the lift transformers. Harmonic currents from the lifts cause overloading by increasing the total RMS current into the transformers.

At the same time, harmonic currents also decrease the current capacity of the transformers, because one Ampere of high frequency current causes more heating than does one Ampere of fundamental frequency current. A procedure for determining actual transformer capacity for a given harmonic load current is given in IEEE standard C57.110-1986. In this case, the reduction is transformer capacity is not significant (1 - 2%), because the transformers are oil-filled. Dry-type transformers on the other hand, would require significant derating if subjected to the same harmonic load current.

Considering both the increase in RMS load current and the decrease in transformer capacity, it is estimated that the peak loading on the 1100HP/250 HP #2 lift transformer is about 111% of its derated capacity. The peak loading of the 900 HP #1 lift and the 900 HP #2 lift transformers are about 137% and 134%, respectively.

However, the measurements also show that these transformers are not being overloaded on a continuous basis. When this is considered along with the low ambient temperatures and short duration of the overloading (30 seconds or less), it is unlikely that the transformers are being subjected to excessive temperature rise. As noted above, these transformers have operated for 15 years without problems. Therefore, like 480 V bus THD, transformer overloading was not considered to be a critical requirement for the filter design.

Comparison of Filter Performance

Table 1 shows that either filter option would be effective in reducing harmonic current levels at the PCC to the levels recommended by IEEE 519. However, the distribution filter option would provide little reduction in 480 V bus voltage distortion (Table 2), and would not be effective at all in reducing lift transformer overloading (Table 3).

Table 1: Effect of filters on harmonic current at the PCC

Harmonic	Limit	None	Dist	Lift
3	7.0%	0.7%	0.9%	1.0%
5	7.0%	10.3%	3.5%	3.7%
7	7.0%	2.6%	1.9%	2.2%
11	3.5%	4.0%	2.6%	0.7%
13	3.5%	2.8%	1.3%	0.6%
17	2.5%	3.8%	0.9%	1.7%
19	2.5%	0.9%	0.5%	1.0%
23	1.0%	0.3%	0.3%	0.3%
25	1.0%	0.1%	0.1%	0.1%

Table 2: Effect of filters on peak voltage distortion levels

	Filter Option		
%VTHD	None	Dist	Lift
12.47 kV Fdr	10.5%	4.3%	4.6%
100/250 HP	12.5%	7.3%	3.4%
900 HP #1	19.2%	14.7%	6.1%
900 HP #2	19.7%	15.0%	6.3%

Table 3: Effect of lift filters on lift transformer loading

Lift Filters ->		No	Yes
Lift	Duty	Xfmr current (% of derated capacity)	
1100/250 HP	Continuous	93.1%	85.3%
	30 Sec	110.9%	93.7%
900 HP #1	Continuous	93.6%	71.7%
	30 Sec	137.3%	107.0%
900 HP #2	Continuous	86.0%	66.3%
	30 Sec	134.2%	104.4%

480 V Filter Design

As previously noted, this option calls for applying filters at the three locations with the largest harmonic load: the 1100 HP / 250 HP lift transformer and both 900 HP lift transformers. Filtering three out of eleven 480 V buses is sufficient to meet with IEEE 519 current limits. The less important objectives of reducing 480 V bus voltage distortion and lift transformer overloading are also achieved.

None of the lift filters employ seventh harmonic stages. Necessary here to make the 480 V filters more cost competitive with the distribution filter alternative, this is not normally recommended. Fortunately, the levels of seventh harmonic current injected by the lift drives are relatively low, therefore it is not necessary to attenuate seventh harmonic current to achieve IEEE 519 compliance.

However, care must be taken to prevent amplification at the seventh harmonic, which can occur if steps are taken to control the resonant peak that falls between the fifth and eleventh harmonics. As shown in Figure 6, the peak is kept above the eighth harmonic for all three filter locations. This was done by sizing the fifth harmonic filters sufficiently large in relation to the eleventh harmonic filters to push the parallel resonance to a higher frequency.

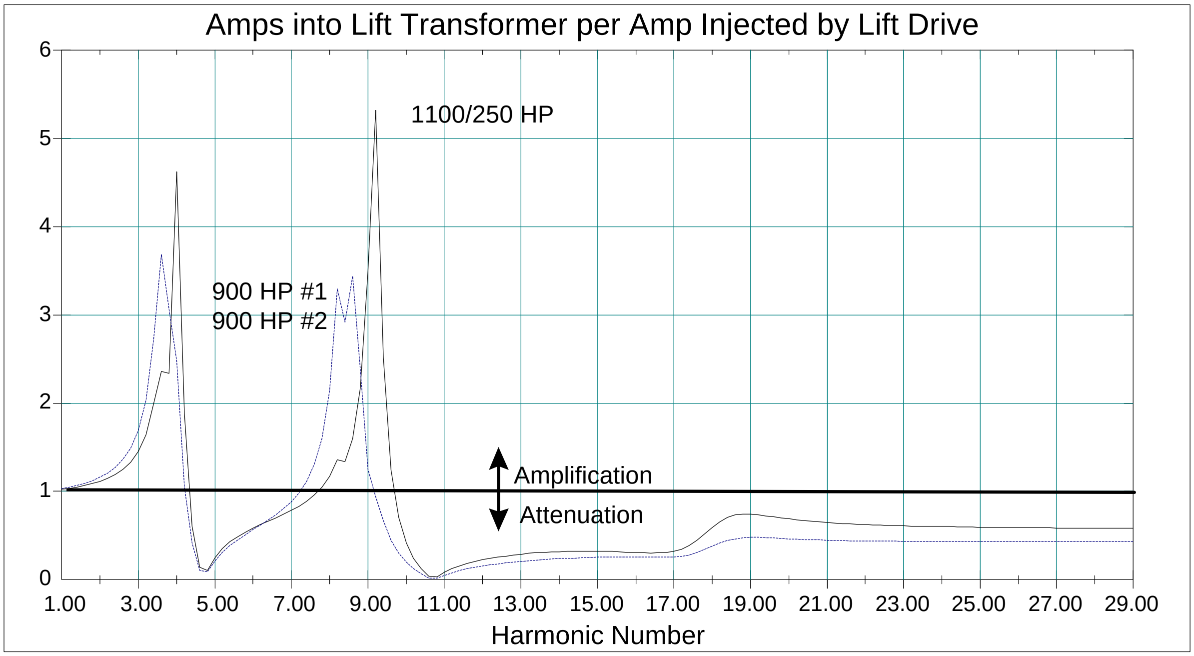


Figure 6: Current amplification at the lift transformers with 480 V filters

480 V Filter Duties

As previously noted, the instrument used to measure harmonic currents at the ski lifts recorded peak and average values once every five minutes. The 480 V filters were sized on the assumptions that the filters will be subjected to the highest five minute average current continuously, with 30 second overloads occurring once every 10 minutes. The measurement data shows that these are conservative assumptions.

480 V filters are not as susceptible as distribution filters to harmonic overload because, from the perspective of other sources on the system, the inductance of the lift transformers is in series with the filter inductance. This lowers the apparent filter tuning with respect to these sources, reducing the harmonic currents that are drawn across the lift transformers.

Observe from Table 4 that the capacitor RMS current duties are high for the eleventh harmonic stages. However, kvar can not be added to the eleventh harmonic filter, as doing so would push the resonant peak too close to the seventh harmonic. The result would be a decrease in eleventh harmonic current duty in the filter, but seventh harmonic current duty would go up. The duties shown in the table are the best that can be achieved.

Table 4: Distribution filter capacitor duties

Duty ->		kV_{RMS}		kV_{Peak}		I_{RMS}	
Limit (% Rated) ->		110%		120%		180%	
Lift	Filter	Continuous	30 Sec	Continuous	30 Sec	Continuous	30 Sec
1100/250 HP	5th	94.0%	94.5%	106.3%	108.9%	122.7%	130.6%
	11th	89.3%	89.4%	92.6%	92.8%	127.5%	138.1%
900 HP #1	5th	94.0%	95.0%	105.8%	110.4%	122.5%	141.5%
	11th	89.5%	90.0%	96.1%	98.4%	130.3%	157.2%
900 HP #2	5th	93.9%	94.9%	105.2%	110.2%	119.9%	140.2%
	11th	89.4%	90.0%	95.9%	98.3%	126.7%	155.5%

The duties shown in the table are based on “continuous” and “30 second” current injections that are 110% of the maximum measured values, with source voltage simultaneously 10% above nominal.

The currents duties indicate that high capacity reactors are required. The filter design specification required that the reactors be able to withstand a continuous RMS current corresponding to 170% of capacitor rating for the fifth harmonic cells, and 180% of capacitor rating for the 11th harmonic cells. The reactors are required to have thermal sensors imbedded in the reactor windings to provide overload protection, as shown in Figure 3. In order to prevent nuisance trips, it is specified that the overload circuits must not trip the filters for continuous currents less than 85% of the reactor ratings.

As discussed previously, the fifth harmonic filters must be divided into two parallel cells to prevent excessive change in fundamental bus voltage when the filter is switched. It is not necessary to divide the eleventh harmonic filters, and with RMS current duties so high, it is not even desirable. Unless the two cells are tuned very close to each other, the cells will not carry equal harmonic current, and one of the cells could be overloaded. If parallel cells are used, the tuning frequencies in each cell should be within 3 Hz of the specified frequency.

Distribution Filter Design

Unlike most large utility customers, ski resorts don’t own a medium voltage distribution system. Medium voltage filters are possible only with cooperation between the resort and the utility. The two parties must have a clear understanding as to what will be done if something goes wrong - e.g., if the filter does reduce harmonic levels sufficiently, or if the filter fails after the manufacturer’s warranty period has expired.

Filter failure due to growth of harmonic loads on the system is a particularly sticky issue. The customer may have caused the failure by adding the new equipment, but it was the utility who had complete control of the filter design. Under those circumstances, insuring that the filter is protected against harmonic overload is very important. However, overload protection of medium voltage filters is not straightforward. Methods of overload protection are discussed in detail below.

Another concern with applying filters on the distribution system is that an unfavorable resonance may be created if there is significant capacitance in the system (power factor banks or cables). This concern is illustrated in Figure 7, which compares the current amplification characteristic of the system without filters (i.e., the curve of Figure 2) with the current amplification character that would result if fifth and seventh notch filters were installed at node J in Figure 1.

Applying the notch filters shifts the parallel resonance from the 16th harmonic to the 19th harmonic, increasing amplification at the 19th harmonic from 2.2 to 7.0. This example illustrates that it is difficult to achieve IEEE 519 compliance on a system with significant capacitance (power factor banks or cables) using notch filters. Adding additional notch filters (11th, 13th, etc.) may be a solution, albeit a costly one.

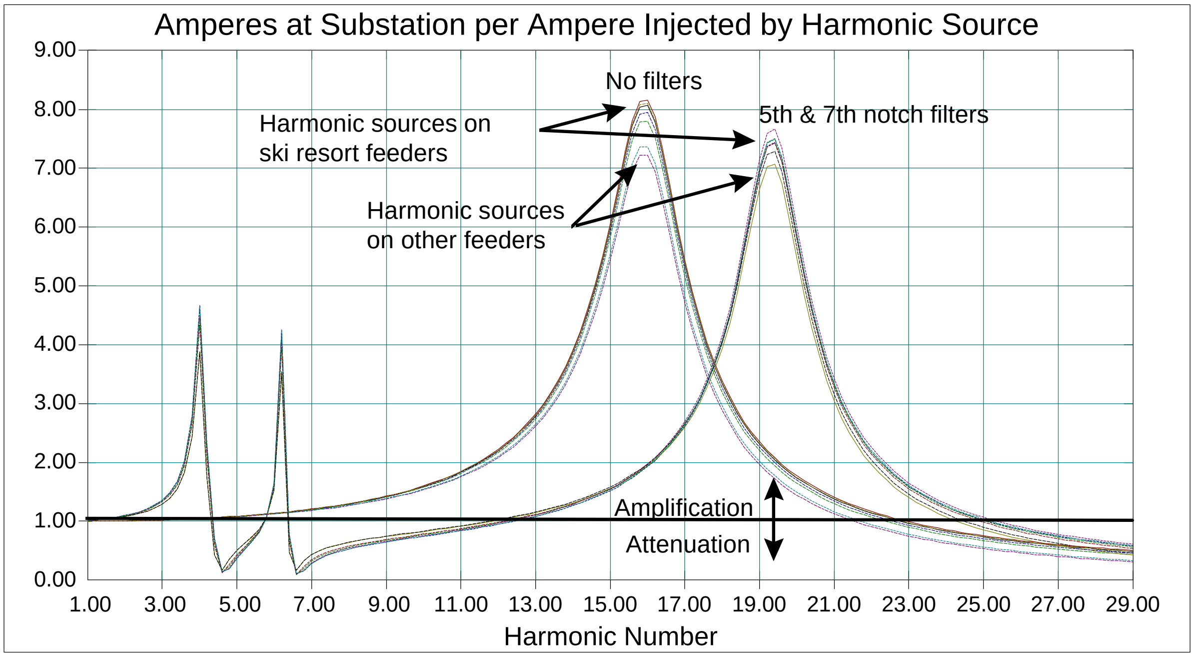


Figure 7: Current amplification at the distribution substation with and without 5th & 7th 12.47 kV notch filters

The distribution filter design developed in this study employs a fifth harmonic notch filter and a seventh harmonic high-pass filter. As shown in Figure 4, the high-pass filter is similar to a notch filter, but has a resistor in parallel with the reactor in each phase. The system current amplification factor with this design is illustrated in Figure 8. Note that the amplification at the harmonics of concern (5, 7, 11, 13, 17, 19, 23 & 25) is reduced to 1.25 or less. On the negative side, we see that converting the seventh harmonic filter to high-pass almost completely eliminates its effectiveness in attenuating the seventh harmonic, but as previously noted, attenuation is not needed in this system to meet IEEE 519.

The total three-phase 60 Hz power loss associated with the resistors is about 4 kW. To reduce the cost of this loss, a time-control relay is recommended to switch the filters off between 6:00 PM and 7:30 AM. Assuming that the filter is energized 10.5 hours a day for 120 days a year, the annual cost of the loss would be $307 at 6¢ per kWh.

The optimum location for the distribution filters is labeled as node J in Figure 1. This is the location which minimizes the total Ampere-feet traveled from all the ASDs to the filter.

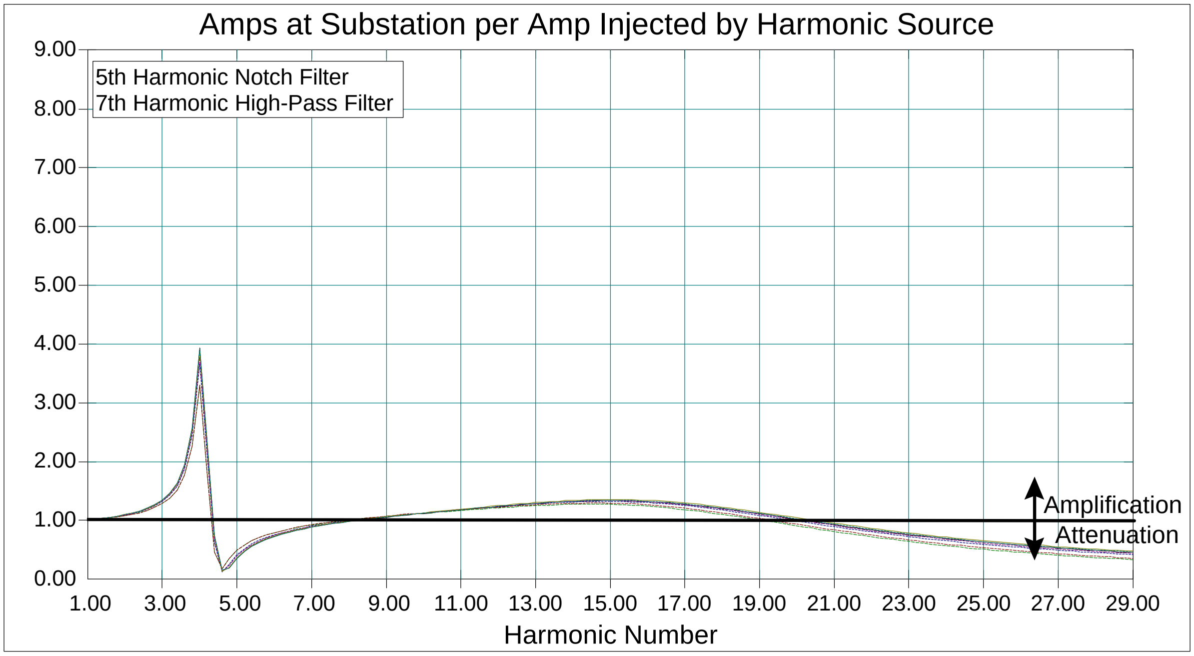


Figure 8: Current amplification at substation with proposed 12.47 kV filter design

Distribution Filter Duties

Because of the concern for harmonic overload due to load growth on the system, selection of filter component values reflects a high degree of conservatism. The capacitor duties shown in Table 5 are based on all lift drives simultaneously at 125% of rated load, and with no phase angle diversity between the harmonic currents injected into the system by the drives and the residential harmonic sources.

Table 5: Distribution filter capacitor duties

	kV_{RMS}	kV_{Peak}	I_{RMS}
Limit	110%	120%	180%
C5	78.9%	91.0%	127.7%
C7	75.8%	78.8%	127.0%

Distribution Filter Overload Protection

Unlike low voltage filters, thermal sensors can not be imbedded in the reactor windings, as this would degrade reactor BIL excessively. Instead, a thermal sensor can be attached to the iron core, or current relays can be used as discussed below.

Induction Disk Relay

This type of relay responds to total RMS (fundamental + harmonic) current. Because the fundamental current is such a large part of the RMS current, it takes a substantial increase in harmonic current to significantly change the RMS current. Therefore, if induction disk relays are used, the filter components must be designed to tolerate harmonic currents that are much higher than the maximum expected.

In order to illustrate this point, let us consider applying induction disk relays to the distribution filters proposed in this study. The fifth harmonic filter and high pass filter will have separate sets of relays, as illustrated in Figure 4.

First, note that since these filters are designed for low reactive compensation, the filter fundamental currents are smaller in proportion to the harmonic currents than in most filter applications. This makes our task easier, and we make it easier still by specifying large margins between the maximum expected harmonic currents and the harmonic currents that the filter components are designed to carry: 55% for the fifth harmonic filter, and 69% for the high-pass filter. These values give a margin of 30% RMS current in each filter, as can be seen in the bottom row of Table 6.

In reality, the RMS current margins are lower. The column labeled T(h)/T(1) in Table 7 shows that the torque induced per Ampere of current in the induction disk relay decreases as the frequency of the current is increased. (These values were taken from an example described in reference [1] - an aluminum disk 9.6 cm in diameter and 2 mm thick.) The maximum expected currents and filter design currents of Table 6 are multiplied by T(h)/T(1) to give the corresponding value of effective current in Table 7. The values in the bottom row of the table show that the effective margins between maximum expected current and filter design current have been reduced from 30% to less than 26% for the fifth harmonic filter, and less than 17% for the high-pass filter.

Table 6: Actual filter harmonic currents

	Fifth Harmonic Filter		High-Pass Filter	
H	Max Expected	Filter Design	Max Expected	Filter Design
1	82.0	82.0	40.3	40.3
2	0.9	1.4	0.4	0.6
3	5.5	8.5	1.8	3.0
4	18.3	28.4	3.1	5.3
5	75.8	117.5	3.7	6.2
6	0.9	1.4	0.3	0.5
7	15.3	23.6	8.8	14.8
9	0.8	1.2	0.8	1.4
11	11.5	17.8	17.0	28.8
13	6.8	10.5	12.7	21.4
15	0.1	0.1	0.1	0.2
17	5.9	9.1	15.1	25.5
19	3.6	5.6	10.5	17.8
23	2.1	3.3	7.6	12.9
25	1.3	2.1	5.2	8.8
RMS Harm	81.1	125.8	31.3	52.9
RMS Fund+Harm	115.4	150.1	51.0	66.5

Table 7: Filter harmonic currents measured by induction disk relay

	T(h)	Fifth Harmonic Filter		High-Pass Filter	
H	T(1)	Max Expected	Filter Design	Max Expected	Filter Design
1	100.0%	82.0	82.0	40.3	40.3
2	95.8%	0.9	1.4	0.4	0.6
3	92.2%	5.1	7.8	1.6	2.8
4	89.0%	16.3	25.3	2.8	4.7
5	86.0%	65.2	101.1	3.2	5.4
6	83.0%	0.8	1.2	0.2	0.4
7	80.2%	12.2	19.0	7.0	11.9
9	74.7%	0.6	0.9	0.6	1.1
11	69.5%	8.0	12.4	11.8	20.0
13	64.6%	4.4	6.8	8.2	13.9
15	60.1%	0.0	0.1	0.1	0.1
17	55.9%	3.3	5.1	8.4	14.2
19	52.0%	1.9	2.9	5.5	9.3
23	45.1%	1.0	1.5	3.4	5.8
25	42.1%	0.6	0.9	2.2	3.7
RMS Harm		69.2	107.3	19.9	33.6
RMS Fund+Harm		107.3	135.1	44.9	52.5

The pickup current for each set of relays is found by multiplying the CT ratio by the relay tap setting. To prevent nuisance trips, this value must be greater than the maximum expected current by some margin to account for relay tolerance. Three percent might be sufficient for a pure 60 Hz current. For the sake of argument, let us suppose that at least 10% is necessary in this case, because the relays that would actually be used might have a different harmonic response than the example upon which we have based our calculations.

With a 10% margin, the desired pickup currents are $1.10 \cdot 107.3$ A = 118.0 A for the fifth harmonic filter, and $1.10 \cdot 44.9$ A = 49.4 A for the high pass filter. Luckily, we are able to select a combination of CTs and tap settings (Table 8) that produce almost exactly the desired pickup currents:

Fifth harmonic filter: 4.0 x 150:5 = 120
High pass filter : 2.5 x 100:5 = 50

Table 8: Relay pickup currents for various CT ratios and tap settings (combinations selected for the filters are shown in bold)

	Relay CT Ratio				
Relay Tap	*100:5*	*150:5*	*200:5*	*250:5*	*300:5*
0.5	10	15	20	25	30
0.6	12	18	24	30	36
0.7	14	21	28	35	42
1.0	20	30	40	50	60
1.2	24	36	48	60	72
1.5	30	45	60	75	90
2.0	40	60	80	100	120
2.5	**50**	75	100	125	150
3.0	60	90	120	150	180
4.0	80	**120**	160	200	240
5.0	100	150	200	250	300
6.0	120	180	240	300	360

The filter RMS design currents should be greater than the actual relay pickup currents by the same 10% margin - 132 A for the fifth harmonic filter, and 55 A for the high-pass filter. As the bottom row of Table 7 shows, the high pass filter design current - with its 69% harmonic overload margin - is not sufficient!

On the other hand, the fifth harmonic filter design current (55% harmonic overload margin) is adequate - barely. It would have to be increased in most other cases, either because the fundamental component will be a larger fraction of the RMS current, or because the available CT ratios and relay tap settings will not yield a pickup current so close to the desired value.

Digital Relay

The principal concern here is that relays which are not designed to measure distorted current are sometimes misapplied to harmonic filters. The consequences can be quite unpleasant.

A digital relay that measures true RMS current is better than the induction disk relay in that its sensitivity is not affected by frequency. Also, unlike the induction disk relay, the pickup current can be set exactly to the value desired.

In the example just discussed, we see that eliminating the frequency correction for the measured current would be a major improvement for relays used for the high pass filter. However, for protecting the fifth harmonic filter, the digital relay is not much better than the induction disk. This is because RMS current, however measured, does is relatively insensitive to changes in harmonic current.

However, there are relays on the market that compute in real time quantities such as current THD and K-factor, and can generate a trip signal if one of these quantities exceeds a user-programmable value. (I include in this category panel-mounted power monitors which can initiate relay trip signals.) K-factor is the most suitable parameter to monitor for filter protection, as it increases faster with harmonic current than does either RMS current or THD.

References:

[1] "Impact of Harmonics on Home Appliances", June 1981. Prepared for the U.S. Department of Energy by the University of Colorado Department of Electrical Engineering, E.F. Fuchs, Principal Investigator.

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