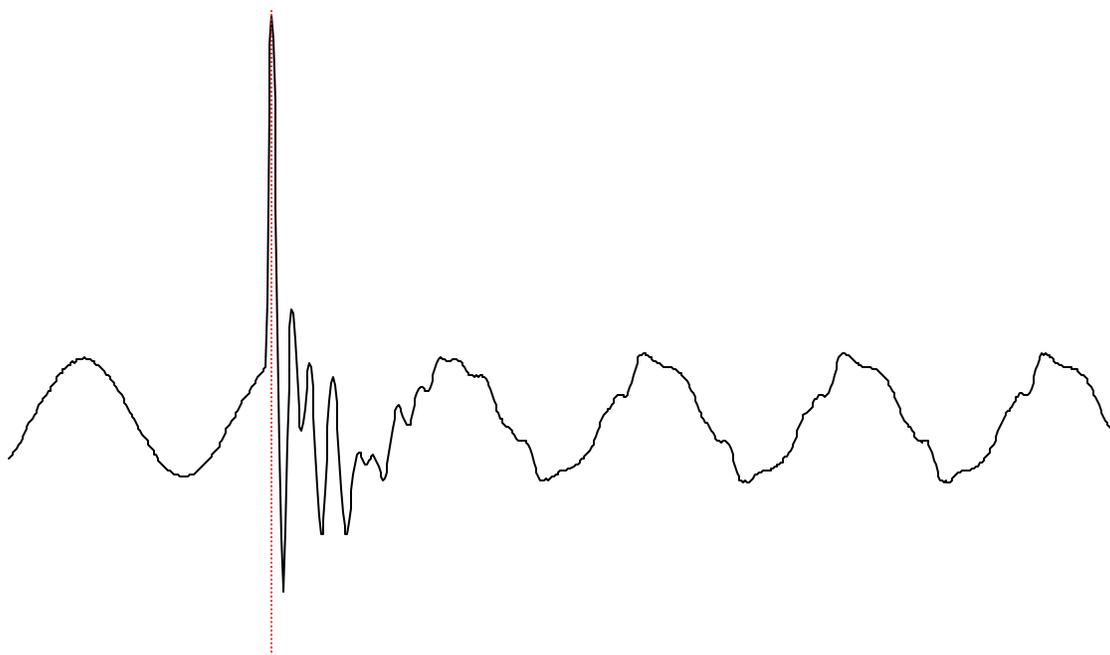


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Harmonics and Transients Tech Notes



Issue # 00-3

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Editor: Karen Brown

Project Manager: Tom Grebe

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Letter from the Editor:

Dear PATH Members:

Welcome to the final edition of *Tech Notes*.

On November 2, 2000 a letter was sent to each one of you telling of Electrotek's decision to change the structure of the PATH User Group for the next year. The decision was based upon providing you, as PATH members, services tailored more specifically to your individual needs. This new service will provide you the ability to select those items that are appropriate for you.

The options that will be provided for the coming year are the following:

- SuperHarm® harmonics analysis software
- SuperHarm® annual maintenance contract that will offer upgrades and bug fixes
- Consulting support that can be purchased for a user-determined number of hours
- Web-based Technical Resource Area that would include access to such features as the PATH Forum
- EMTP Workbook
- HarmFlo+ Workbook
- EMTP Lab Book
- Filter Design Spreadsheet
- TOP2000 — This, of course, has been available to you free-of-charge and will continue to be so.

If you have questions concerning this new format, please call Dave Mueller +1 865-470-9222 x132 or Tom Grebe at x133. You may also email inquiries to Dave at davem@electrotek.com or Tom at tgrebe@electrotek.com.

We of Electrotek Concepts have appreciated your participation in PATH and hope to serve you in the future with a new PATH User Group that is better serves your needs.

Sincerely,



Karen Brown
Technical Coordinator
Editor, PATH Users Group / PQView User Group

THE ATP PACKAGE: NEW CAPABILITIES AND APPLICATIONS

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Abstract: The ATP is a powerful and flexible tool widely used in many types of applications. Users can take advantage of capabilities from several programs to design a custom-made package. This paper presents a summary of the main solution methods and capabilities of this package, with emphasis on the new options and applications.

Keywords: Digital Simulation, Modeling, Transient Analysis, Harmonic Analysis, Sensitivity Analysis, Statistical Analysis, ATP, ATPDRAW, TOP.

Introduction

ATP is an acronym that stands for Alternative Transients Program [1]. This tool was originally developed for simulation of transients in power systems. During the last years several tools has been designed to help ATP users. These programs can be integrated in a single package that can be customized for a specific application.

An ATP simulation consists of several steps. One or several programs can be currently used in each step.

- ATPDraw [2] for creating/editing input files
- TPBIG for transients and harmonics simulations
- PCPLOT, TPLOT, GTPLOT, or PLOTXY for plotting.

ATPDraw is an interactive Windows-based preprocessor that can act as a shell for the whole package. Users can control the execution of all programs integrated in the package from ATPDraw. This tool supports ATP standard components. In addition, users can also create custom-made objects based on ATP capabilities such as Data Base Module and MODELS language [1], [2]. By creating new objects and adding programs that can be controlled from ATPDraw, users can design a package to support specific studies.

ATP capabilities are regularly updated and expanded. Several of the capabilities recently implemented are especially adequate for studies not covered up to now, i.e. harmonics propagation, sensitivity studies, or statistical (Monte Carlo) simulations. The ATP package is made of three tools: ATPDraw, TPBIG, and TOP (The Output Processor) [3]. This paper presents a summary of ATP capabilities and solution methods, an introduction to the type of studies that can be performed with this package, and an overview of its applications.

The ATP Package

Figure 1 shows the sequence of main tasks performed in a normal study by the programs integrated in the ATP package. In fact, the programs manipulate many other files, and many more interactions between programs and files are usually activated. The subsequent sections provide a short description of each tool.

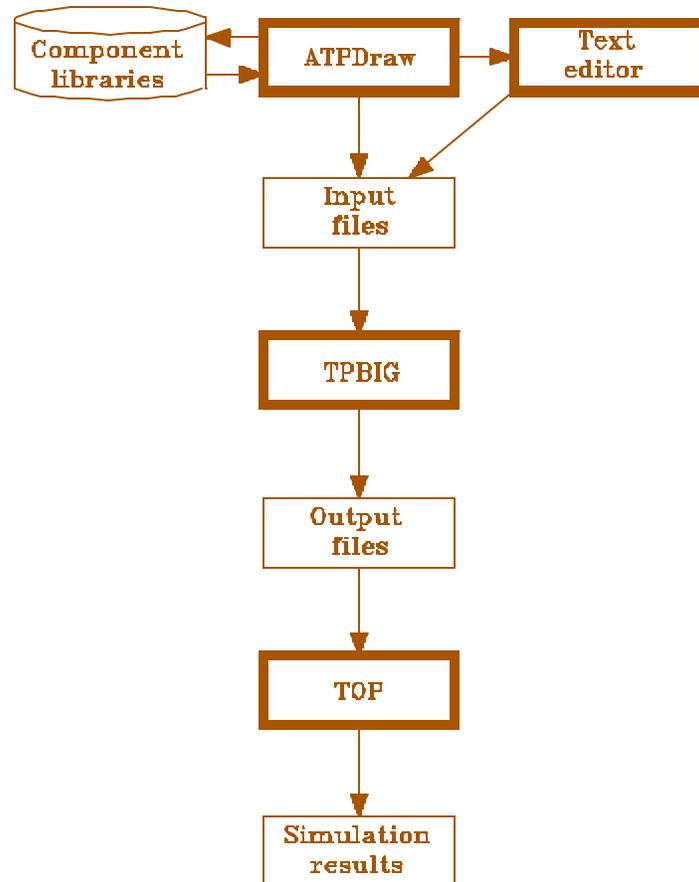


Figure 1: Main Tasks of the ATP Package

ATPDRAW

ATPDraw [2] is an interactive graphical preprocessor developed to create and edit the data file of the system to be simulated. The user can build an electric circuit by selecting predefined components from the available menu. The program creates the corresponding data file in ATP code. The program automatically administrates node naming. However, the user may assign names to selected nodes. All tools of the package can be run from the

ATPDraw menu. Users are also allowed to edit and add other batch jobs that can expand the capabilities of the package.

Main ATPDraw options are summarized below

- Built-in editor for creating and correcting data files
- Support of Windows clipboard for metafile/bitmap
- Output of Windows metafile/bitmap file format or PostScript files
- Copy/paste, rotate, import/export, group/ungroup, undo, print facilities
- Help on line
- Icon editor for user specified objects
- Multiple windows.

The types of files that can be manipulated by this tool are many

- Circuit files in binary code, where the program stores the information about the equivalent graphical picture of circuits
- Input files in ACSCII code, created as input for ATP simulations
- Support files for ATPDraw objects in binary code; they specify the data and nodes for an object with the icon and help information included
- Files created by DATA BASE MODULE and called by user specified objects
- MODELS files in ASCII code, where the description of a model is contained.

TPBIG

TPBIG [1] is a tool for digital simulation of electromagnetic transients in power systems. In addition to the modeling capabilities, several non-simulation supporting routines are available to create model data files. These supporting routines can be used for computation of line parameters or derivation of coupled RL matrix aimed at representing multi-phase, multi-winding transformers.

A TPBIG simulation is carried out with a fixed time step selected by the user, using the trapezoidal rule of integration. Although this program is mainly intended for transient simulation, it can also be used to perform AC steady state calculations, to obtain a system impedance as a function of the frequency (FREQUENCY SCAN) and to calculate harmonic power flows.

TOP

TOP [3], The Output Processor® is a Windows-based tool that reads data from a variety of sources and transforms it into a high quality graphics for inclusion in reports and documents. The capabilities of this program allow a user to

- Handle data from various sources
- Visualize the data of interest in the form of tables and graphs
- View several plots in multiple windows simultaneously; in addition, the user can move, size, and arrange the windows on the screen
- Display selected data using *windows* (one or more quantities plotted on the same axis) and *frames* (multiple sets of axes in one window)
- Perform mathematical operations on the various data objects supported by the program by means of a post-processing feature, "TOPCalc"
- Format the data display based on user preferences
- Export the data being visualized in a window to a variety of other formats.

This tool can be used not only for visualization but also for some post-processing tasks, for instance Fourier analysis or calculation of some power quality indices, i.e. THD.

Basic Solution Methods

Time-Domain Solution

It is based on the Dommel's scheme that combines the trapezoidal rule and the Bergeron's method [4]. The trapezoidal rule is used to convert the differential equations of the network components into algebraic equations involving voltages, currents and past values. These algebraic equations are assembled using a nodal approach

$$[\mathbf{G}][\mathbf{v}(t)] = [\mathbf{i}(t)] - [\mathbf{I}] \quad (1)$$

where $[\mathbf{G}]$ is the nodal conductance matrix, $[\mathbf{v}(t)]$ is the vector of node voltages, $[\mathbf{i}(t)]$ is the vector of current sources, and $[\mathbf{I}]$ is the vector of "history" terms. The conductance matrix is symmetrical and remains unchanged as the integration is performed with a fixed time-step size. The solution of the transient process is then obtained using triangular factorization.

Two methods are generally used to solve nonlinear networks: pseudo-nonlinear representation of power components and compensation. Using the first approach, the conductance matrix is changed and re-triangularized whenever the solution moves from one straight-line segment to another. Using compensation, nonlinear elements are represented as current injections that are superimposed to the solution of the linear

network after this solution has been computed. This second approach is usually very efficient but it is limited to only one nonlinear component per isolated sub-network.

In switching operations or transitions between segments in piecewise-linear inductances, the trapezoidal rule acts as a differentiator, and introduces sustained numerical oscillations. These oscillations can be avoided by adding damping to force them to decay or placing snubber (RC) circuits in parallel with switches. The latter technique is very useful for simulating variable topology converters.

Frequency-Domain Solution

It is based on the ac steady state solution of linear networks. For a single frequency this solution is obtained using nodal admittance equations [4]

$$[\mathbf{Y}][\mathbf{V}] = [\mathbf{I}] \quad (2)$$

which are elements of $[\mathbf{Y}]$, $[\mathbf{V}]$ and $[\mathbf{I}]$ complex phasor values.

Two ATP features, Frequency Scan (FS) and Harmonic Frequency Scan (HFS) are also based on this method. FS allows for a repetitive solution of the steady-state phasor solution as the frequency of the sinusoidal source is varied between given limits. HFS is a capability based on the same approach as many harmonic analysis programs and uses the same solution method that FS, it can be applied to harmonics propagation analysis in power networks by executing a string of phasor solutions determined by the list of user-specified ac sources [5].

This solution method cannot be applied in the presence of nonlinear components or variable topology circuits, which can produce steady-state harmonics. Some simple approaches can be then used. The simplest one is known as "brute force": the system is started from standstill and the simulation is carried out long enough to let the transients settle down to steady-state conditions. This approach can have a very slow convergence if the network has components with light damping. A more efficient method is to perform an approximate linear ac steady-state solution with nonlinear branches disconnected or represented by linearized models. Another alternative is based on the "start again" feature; using a "brute force" initialization, the solution is saved once the system reaches the steady-state, later runs can be started at this point.

ATP Applications

Recent capabilities implemented in the ATP allow users to expand the applications of this tool. The type of applications which can be presently covered by the ATP package have been grouped into the following categories

- a) Time-domain simulations
- b) Frequency-domain simulations
- c) Sensitivity analysis

- d) Statistical analysis
- e) Development of custom-made models.

Time-Domain Simulations

A time-domain simulation is generally used for simulation of transients, such as switching or lightning overvoltages. However, it is also used to analyze harmonic distortion. As mentioned above, the steady state cannot be calculated when the system includes nonlinear components or variable topology converters. The initialization is then performed by starting the system from standstill or by obtaining the steady state of a linearized system. Using both approaches, the simulation has to be carried out to let the program calculate the actual steady state.

Frequency-Domain Simulations

Basically they are applied to obtain the steady state of linear systems and to analyze problems related to harmonics propagation. Frequency Scan is used to obtain the driving point impedance at a particular node versus frequency, detect resonance conditions and design filter banks. Harmonic Frequency Scan will be generally used for analyzing harmonic propagation in power networks. It requires that certain components have frequency-dependent parameters. Some of these components are not yet available in the ATP package, but users can develop custom-made models to meet modeling requirements.

Sensitivity Analysis

The concept sensitivity has been used to denote different types of studies. In this document a sensitivity analysis is performed to evaluate the variation of a variable caused by changes of one parameter. This type of analysis is especially useful when one or more parameters cannot be accurately specified. A sensitivity analysis will determine for which range of values a parameter is of concern. This type of analysis is based on the combination of two new ATP features, Pocket Calculator Varies Parameters (PCVP) and \$PARAMETER. PCVP allows users to repeat a case as many times as desired, \$PARAMETER is used to change a network parameter between a range of values.

Statistical Analysis

Some power quality variations are characterized by parameters that can be statistically described. A Monte Carlo simulation is a numerical procedure applied to problems involving random variables. Statistical switching has been a built-in capability of most transients programs for many years; however, many statistical studies cannot be performed with this capability. PCVP combined with other ATP capabilities, i.e. MODELS, can be used to perform Monte Carlo simulations not covered by statistical switches. An interesting application of some new ATP features to lightning studies was presented in [6].

Development of Custom-Made Models

Many capabilities of the ATP package can be used to develop custom-made models and represent missed components. The new models are generally based on TACS/MODELS capabilities or developed by using Data Base Module.

TACS/MODELS capabilities are used to developed modules aimed at representing control strategies, monitoring devices or protection systems. However the TYPE-94 branch component, which is also based on MODELS language can be very useful in other applications, for instance lightning studies. Data Base Module is a supporting routine that can be used for the development of integrated modules or to create component modules. Data modules are generally developed to simplify the use of power components and extend modeling capabilities to more complex equipment. More powerful modules can be developed when combined with \$PARAMETER, since simple calculations can be performed with module arguments and internal module variables using a pseudo-Fortran language [7].

Table I presents a summary of the type of applications that can be covered with the new capabilities.

Table 1: ATP Applications

<i>TASK</i>	CAPABILITY	APPLICATION
Frequency-domain simulation	TPBIG (Harmonic Frequency Scan, Frequency Scan)	Steady-state initialization Harmonic analysis Resonance analysis
Time-domain simulation	TPBIG	Transient analysis
Multiple run	TPBIG (PCVP, MODELS, Statistical switches)	Sensitivity analysis Monte Carlo analysis
Development of custom-made models	ATPDraw TPBIG (Data Base Module, MODELS)	Harmonic source model Other library modules

Examples

Two simple case studies illustrating some of the new applications that can be covered by the package are described below.

Harmonic Analysis

Figure 2 shows the scheme of the test case, a three-phase linear load, paralleled by a diode rectifier, is fed from the medium voltage side of a step-down transformer. Figure 3 depicts the diagram generated by ATPDraw, showing some custom-made modules for harmonic studies. A 12 MVAR capacitor bank is to be placed at the point of common coupling (PCC) to improve the power factor. After installing the capacitor bank, a resonance problem could be originated due to the presence of harmonic currents injected by the diode rectifier. This problem can be predicted by performing a frequency scan of the system once the capacitor bank has been placed [8]. In this paper it will be analyzed by using the HFS feature, which is based on the same basic approach to harmonic analysis, since it solves the network for sources of the same harmonic order separately [5].

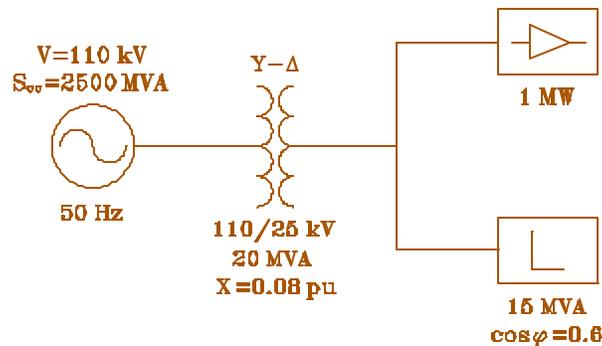


Figure 2: Harmonic Resonance Test Case

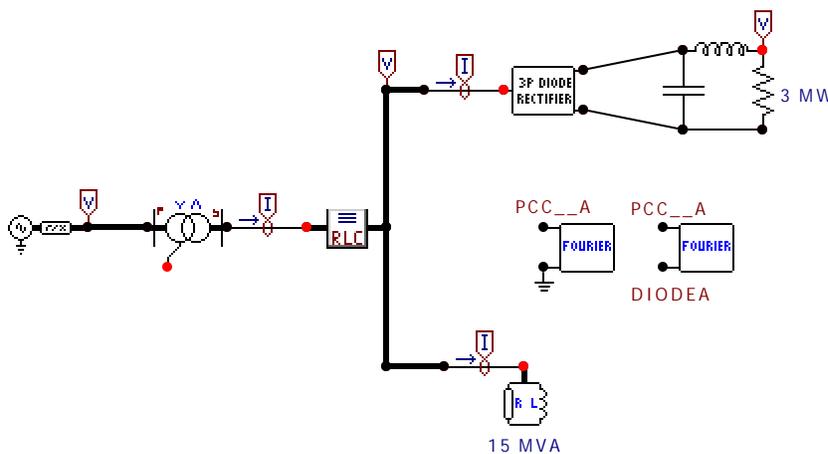


Figure 3: Diagram of the Test Case Generated by ATPDraw

Therefore the diode rectifier will be replaced by 1 A current sources with the same harmonic contents that its ac side current, see Figure 4. The harmonic response once the capacitor bank was installed is presented in Figure 5. The output produced by HFS for this case was the following one

Column headings for the 5 output variables follow. These are divided among the 3 possible FS variable classes as follows:

First column — output variables are electric-network voltage differences (upper voltage minus lower voltage).

Next 4 columns — output variables are branch currents (flowing from the upper node to the lower node).

Only the magnitude of each variable is outputted. This is the default choice, which was not superseded by any request.

Step	F [Hz]	PCC__A	PCC__A	PCC__A	OUT_TA	IN__LA
			DIODEA	LOAD_A	IN__LA	CAPB_A
1	50	2.75195497	1.0	.066046926	.99520453	.052835601
2	250	39.7924788	1.0	.593035586	2.89310539	3.82007228
3	350	12.3219884	1.0	.180626761	.639973934	1.65607397
4	550	5.64914767	1.0	.081943144	.186723041	1.1930996
5	650	4.53218785	1.0	.065605873	.126758667	1.1312338
6	850	3.28693513	1.0	.047477223	.070300838	1.07285543
7	950	2.8988592	1.0	.041846231	.055474486	1.05750366

It is obvious that a resonance problem will be originated by the 5th harmonic. Installing a passive filter instead of the capacitor bank can solve this problem. The frequency response with the passive filter is depicted in Figure 6 and shows the tuning frequency and how the resonance peak is moved to a non-dangerous frequency range. The filter can be used for both improving the power factor and avoiding resonance.

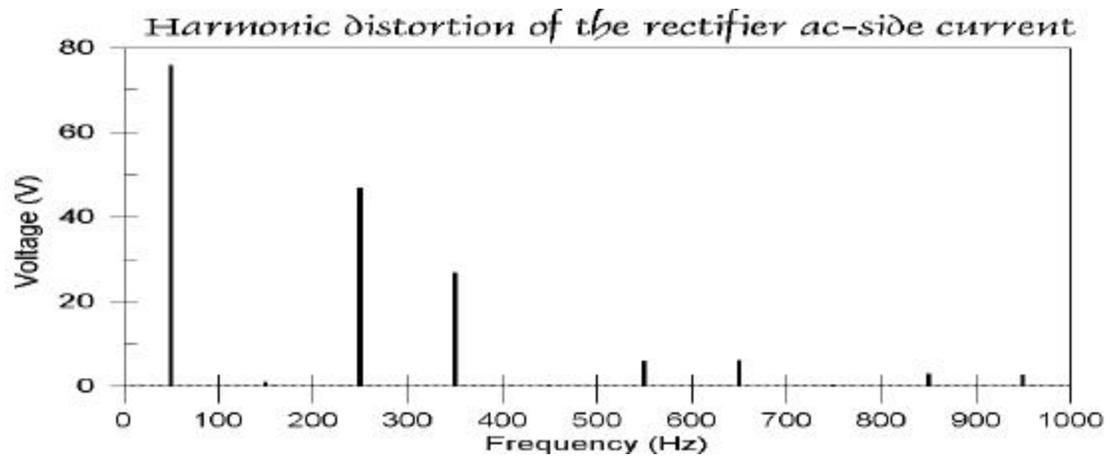


Figure 4: Harmonic Distortion of Rectifier Current

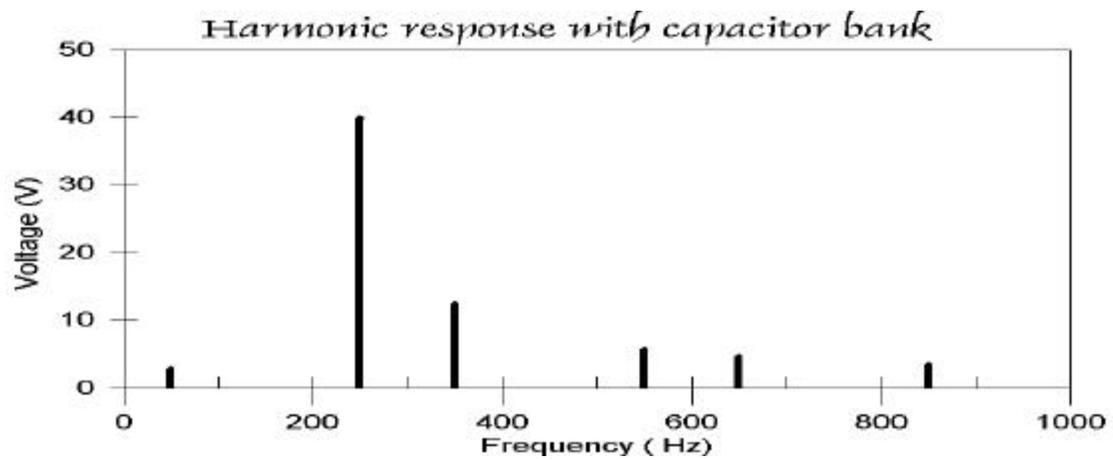


Figure 5: Frequency Response after Installing the Capacitor Bank

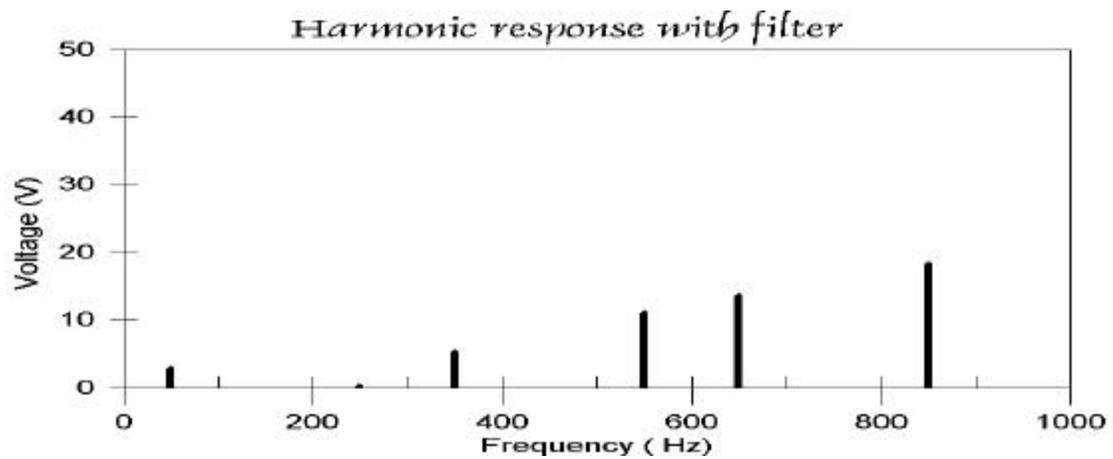


Figure 6. Frequency Response after Installing the Passive Filter

Sensitivity Analysis

Very high resonant overvoltages can occur in parallel transmission lines when they are compensated by means of shunt reactors. Figure 7 shows the diagram of a parallel-line configuration. Consider the following situation [9].

- Circuit 2 is cleared due to a fault, but the shunt reactors remain connected.
- A phase-to-ground fault is originated in circuit 1
- The protection system opens the circuit breaker at the receiving end, but fails to open the circuit breaker at the sending end.

Resonant overvoltages could occur on the de-energized line due to the coupling with the energized line. The value of these overvoltages will depend on the reactive power of the shunt reactors. The aim of a sensitivity analysis is to find out for which range of values of the shunt reactor power a resonance condition could be produced.

Line geometry is shown in Figure 8a. Since the resonance conditions can be analyzed using steady state calculations, the transmission lines are represented with 10-mile pi sections cascaded in series, as shown in Figure 8b. It is also assumed that the transmission lines are transposed every 30 miles.

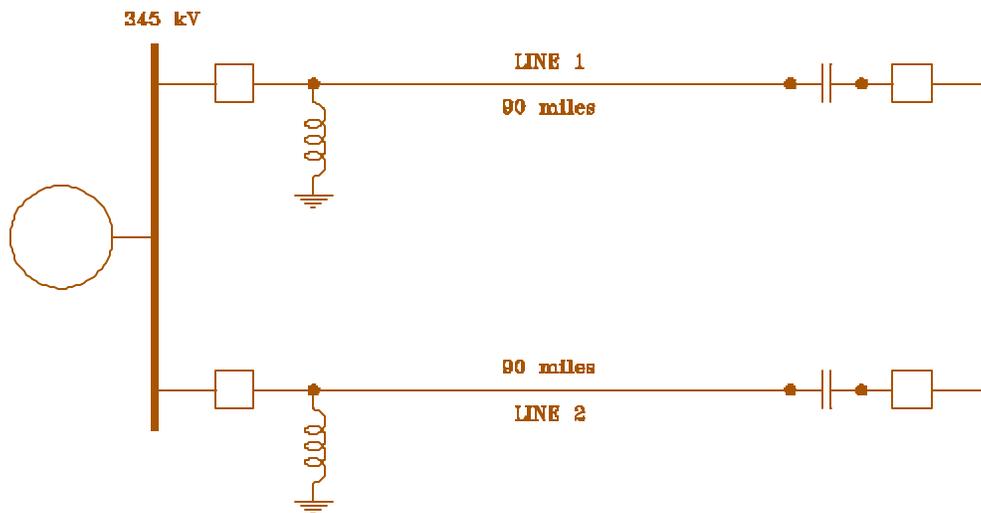
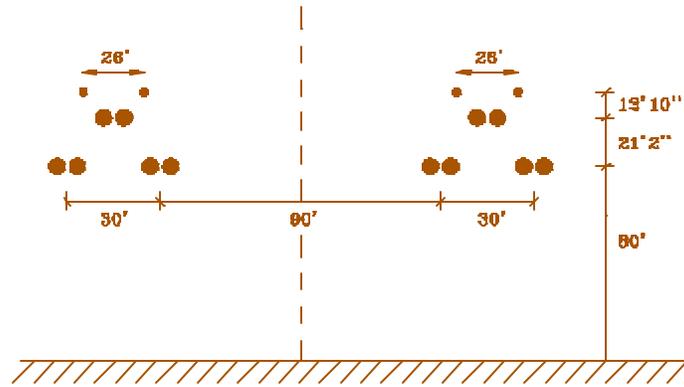


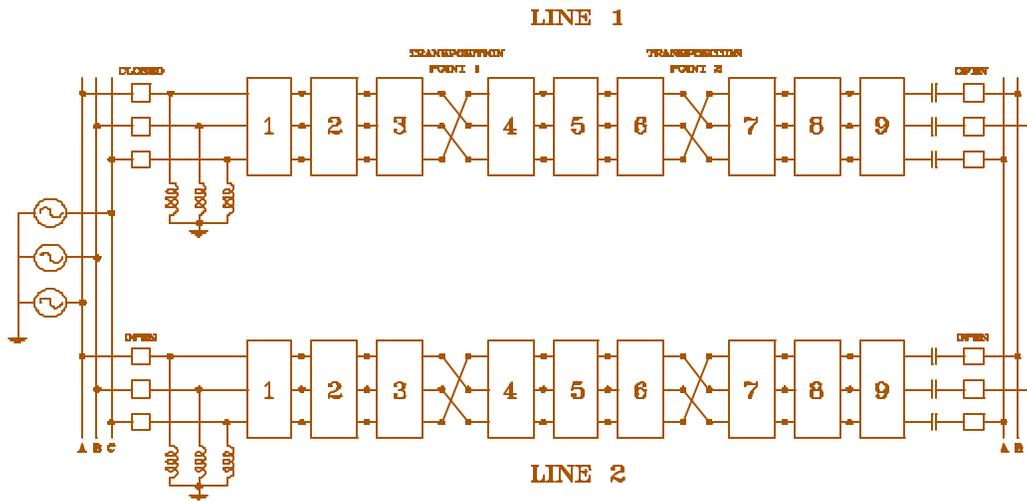
Figure 7: Diagram of the Test Case

Figure 9 shows the voltage at the sending end of circuit 1 as a function of the reactive power of these reactors. One can easily deduced for which range of values resonant overvoltages will be induced on the de-energized line.

There are several solutions to the problem of resonance between parallel lines, as it has been analyzed in this example [9]: avoid reactor powers which could cause resonance, use switches to disconnect shunt reactors from de-energized lines, or install switched reactors in the substation rather than on the lines.



a) Line Geometry



b) Detailed ATP Representation

Figure 8: Parallel Transmission Lines

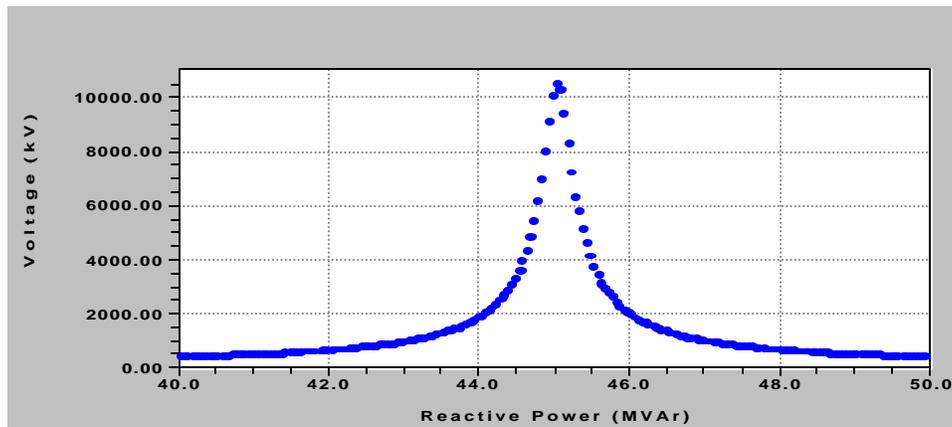


Figure 9. Parallel Resonance $\frac{3}{4}$ Sensitivity Analysis

Conclusions

The ATP is a Windows-based tool that can be applied to an increasing number of studies and customized for specific applications. The version presented in this document consists of three programs, but it is not restricted to them, since integrating more programs in the package can easily expand it. This paper has shown how new ATP capabilities can be used in studies not previously covered by this too.

T. Grebe and S. Smith, "Visualize system simulation and Measurement data," *IEEE Computer Applications in Power*, vol. 12, no. 3, pp. 46-51, July 1999.

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A REVIEW OF UTILITY CAPACITOR SWITCHING

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Introduction

The application of utility capacitor banks has long been accepted as a necessary step in the efficient design of utility power systems. In addition, capacitor switching is generally considered a normal operation for a utility system and the transients associated with these operations are generally not a problem for utility equipment. These low frequency transients, however, can be magnified in a customer facility (if the customer has low voltage power factor correction capacitors) or result in nuisance tripping of power electronic based devices, such as adjustable-speed drives (ASDs). Capacitor energizing is just one of the many switching events that can cause transients on a utility system. However, due to their regularity and impact on power system equipment, they quite often receive special consideration.

Transient overvoltages and overcurrents related to capacitor switching are classified by peak magnitude, frequency, and duration. These parameters are useful indices for evaluating potential impacts of these transients on power system equipment. The absolute peak voltage, which is dependent on the transient magnitude and the point on the fundamental frequency voltage waveform at which the event occurs, is important for dielectric breakdown evaluation. Some equipment and types of insulation, however, may also be sensitive to rates of change in voltage or current. The transient frequency, combined with the peak magnitude, can be used to estimate the rate of change.

There are a number of transient related concerns that are generally evaluated when transmission and distribution shunt capacitor banks are applied to the power system. These concerns include insulation withstand levels, switchgear ratings and capabilities, energy duties of protective devices, and system harmonic considerations. In addition, these considerations need to be extended to include customer facilities due to the increased use of power electronic based end-user equipment. Applications concerns often evaluated include:

- Overvoltages associated with normal capacitor energization
- Open line/cable end transient overvoltages
- Phase-to-phase transients at transformer terminations
- Voltage magnification at lower voltage capacitor banks (including customer systems)
- Arrester duties during restriking events
- Current-limiting reactor requirement
- System frequency response and harmonic injection
- Impact on sensitive customer power electronic loads
- Ferroresonance and dynamic overvoltage conditions

Power quality symptoms related to utility capacitor switching include customer equipment damage or failure, nuisance tripping of adjustable-speed drives or other process equipment, transient voltage surge suppressors (TVSS) failure, and computer network problems.

Transient characteristics are dependent on the combination of the initiating mechanism and the electric circuit characteristics at the source of the transient. Circuit inductances and capacitances — either discrete components such as shunt capacitance of power factor correction banks or inductances in transformer windings, or stray inductance or capacitance because of proximity to other current carrying conductors or voltages — are responsible for the oscillatory nature of transients. Natural frequencies within the power system depend on the system voltage; line lengths, cable lengths, system short circuit capacity, and the application of shunt capacitors.

Energizing a shunt capacitor bank from a predominantly inductive source results in an oscillatory transient that can approach twice the normal system peak voltage (V_{pk}). Figure 1 illustrates the simplified equivalent system for the energizing transient. The characteristic frequency (f_s) of this transient is given by:

$$f_s = \frac{1}{2\pi\sqrt{L_s C}} \approx f_{\text{system}} * \sqrt{\left(\frac{X_c}{X_s}\right)} \approx f_{\text{system}} * \sqrt{\left(\frac{\text{MVA}_{sc}}{\text{MVA}_r}\right)} \approx f_{\text{system}} * \sqrt{\left(\frac{1}{\Delta V}\right)}$$

And the peak inrush current (I_{pk}) is determined using:

$$I_{pk} = \frac{V_{pk}}{Z_s} \quad Z_s = \sqrt{\left(\frac{L_s}{C}\right)}$$

Where:

[Example]

f_s = characteristic frequency (Hz)	[379 Hz]
L_s = positive sequence source inductance (H)	[17.53mH]
C = capacitance of bank (F)	[10.03 μ F]
f_{system} = system frequency (50 or 60 Hz)	[60 Hz]
X_s = positive sequence source impedance (Ω)	[6.61 Ω]
X_c = capacitive reactance of bank (Ω)	[264.50 Ω]
MVA_{sc} = three-phase short circuit capacity (MVA)	[2000 MVA]
MVA_r = three-phase capacitor bank rating (MVA _r)	[50 MVA _r]
ΔV = steady-state voltage rise (per-unit)	[2.5%]
V_{pk} = peak line-to-ground bus voltage (V)	[93897.11V]
Z_s = surge impedance (Ω)	[39.35 Ω]

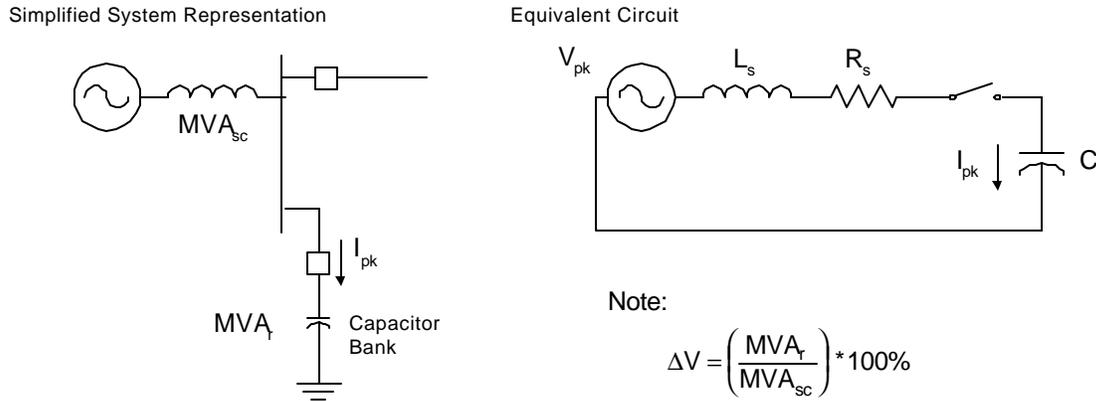


Figure 1: Equivalent Circuit for Capacitor Energizing

Relating the characteristic frequency of the capacitor energizing transient (f_s) to a steady-state voltage rise (ΔV) design range provides a simple way of quickly determining the expected frequency range for utility capacitor switching. For example, a 60 Hz system with a design range of 1.0% to 2.5% would correspond to characteristic frequency range of 380 to 600 Hz. For a shunt capacitor bank on a high voltage bus, transmission line capacitance and other nearby capacitor banks cause the energizing transient to have more than one natural frequency. However, for the first order approximation, this equation can still be used to determine the dominant frequency.

Because capacitor voltage cannot change instantaneously (remembering that $i(t)=Cdv/dt$), energization of a capacitor bank results in an immediate drop in system voltage toward zero, followed by an oscillating transient voltage superimposed on the 60 Hz fundamental waveform. The peak voltage magnitude depends on the instantaneous system voltage at the instant of energization, and can reach 2.0 times the normal system voltage (V_{pk} – in per-unit) under worst-case conditions. The voltage surge is at the same frequency as the inrush current (I_{pk}) and rapidly decays to the system voltage.

For a practical capacitor energization without trapped charge, system losses, loads, and other system capacitances cause the transient magnitude to be less than the theoretical 2.0 per-unit. Typical magnitude levels range from 1.3 to 1.5 per-unit and typical transient frequencies generally fall in the range from 300 to 1000 Hz. Figure 2 illustrates an example (measured) distribution system capacitor-energizing transient.

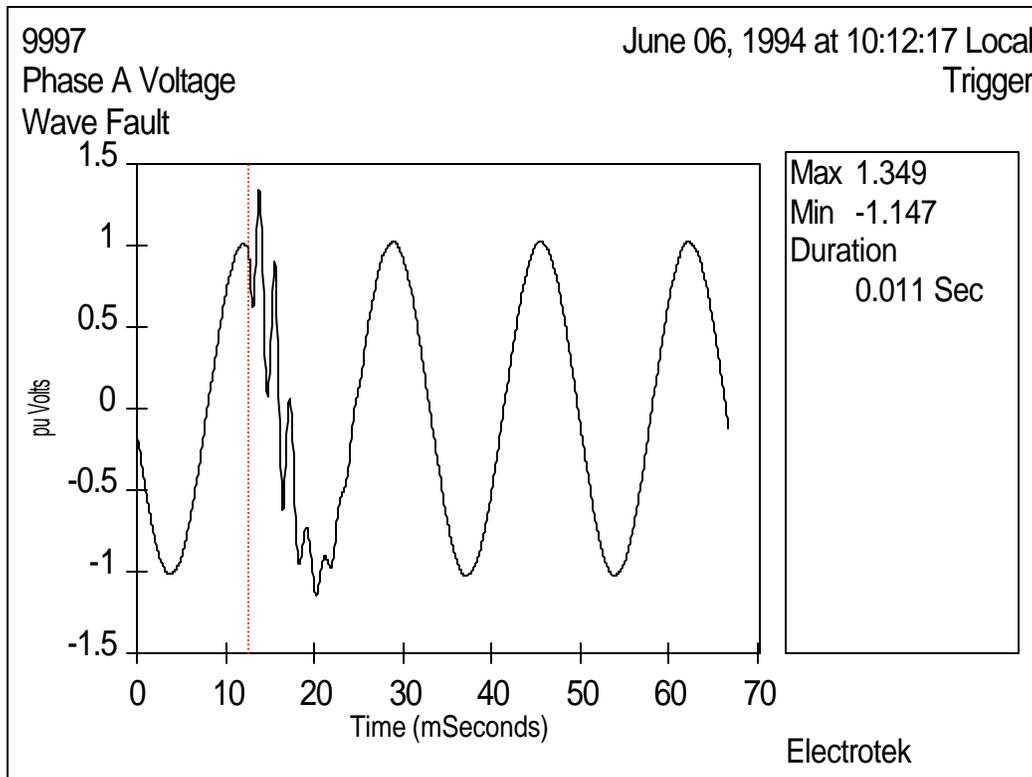


Figure 2: Example Distribution System Capacitor Switching Transient

Overvoltage Mitigation for Capacitor Switching

The technologies currently available for transmission and distribution system transient overvoltage control either attempt to minimize the transient overvoltage at the point of application, or limit (clip) the overvoltages at local and/or remote locations. These devices include:

- Synchronous closing control
- Pre-insertion resistors and inductors
- Fixed inductors
- MOV arresters

Previous studies (digital simulation and TNA) have suggested that the effectiveness of these control methods is system dependent, and that detailed analysis is often required to select the optimum control scheme. While often justifiable for large transmission applications, analysis of distribution system capacitor applications is rarely completed, and in general, banks are installed without transient overvoltage control. Each of these methods, summarized in Table 1, has various advantages and disadvantages in terms of transient overvoltage reduction, cost, installation requirements, operating/maintenance requirements, and reliability.

Additionally, the criteria by which these devices are evaluated have recently gone through a significant change. Previously, evaluating the impacts on utility-side equipment and operations was the primary factor for justifying the additional expenditure. However, due to the adverse impacts on end-use equipment and systems, a number of utilities have recently begun to look for a “transient-free” solution.

Table 1: Summary of Overvoltage Mitigation Devices

Mitigation Technique	Local Overvoltages	Remote Overvoltages	Customer-Side PQ Considerations	Estimated Relative Cost	Install & Maintain
Distribution Level:					
No control	Moderate - High	Moderate - High	Moderate - High	---	---
Pre-insertion resistor	Low	Low	Low - Moderate	Low - Moderate	Moderate
Synchronous closing	Low	Low - Moderate	Low - Moderate	Moderate - High	High
Fixed Inductors	Moderate - High	High - Very High	High - Very High	Low - Moderate	Low
Arresters (MOV & SiC)	Moderate - High	Moderate - High	Moderate - High	Moderate	Minimal
Transmission Level:					
No control	Moderate - High	High - Very High	High - Very High	---	---
Standard pre-insertion inductor	Low - Moderate	Moderate - Very High	Moderate - High	Moderate	Minimal
High-loss pre-insertion inductor	Low	Low - Moderate	Low - Moderate	Moderate - High	Moderate
Pre-insertion resistor	Low - Moderate	Low - Moderate	Low - Moderate	Moderate	Moderate
Synchronous closing (analog)	Low	Low - Moderate	Low - Moderate	Moderate	High
Fixed inductors	Moderate - High	High - Very High	High - Very High	High	Low
Arresters (MOV & SiC)	Moderate - High	Moderate - High	Moderate - High	Moderate	Minimal

Synchronous Closing Control

Synchronous closing is independent contact closing of each phase near a voltage zero, as illustrated in Figure 3. To accomplish closing at or near a voltage zero (avoiding high prestrike voltages), it is necessary to apply a switching device that maintains a dielectric strength sufficient to withstand system voltages until its contacts touch. Although this level of precision is difficult to achieve, closing consistency of ± 0.5 milliseconds should be possible. Previous research has indicated that a closing consistency of ± 1.0 millisecond provides overvoltage control comparable to properly sized pre-insertion resistors. The success of a synchronous closing scheme is often determined by the ability to repeat the process under various (system and climate) conditions. Adaptive, microprocessor-based control schemes that have the ability to “learn” from previous events address this concern. The primary benefits of this capability are the control’s ability to compensate for environmental factors and the increased reliability (less maintenance) that can be achieved.

Grounded capacitor banks are controlled by closing the three phases at three successive phase-to-ground voltage zeros (60° separation). Closing the first two phases at a phase-to-phase voltage zero controls ungrounded banks and then delaying the third phase 90 degrees (phase-to-ground voltage zero).

Figure 4 illustrates an example summary of the local bus transient overvoltage level versus timing error.

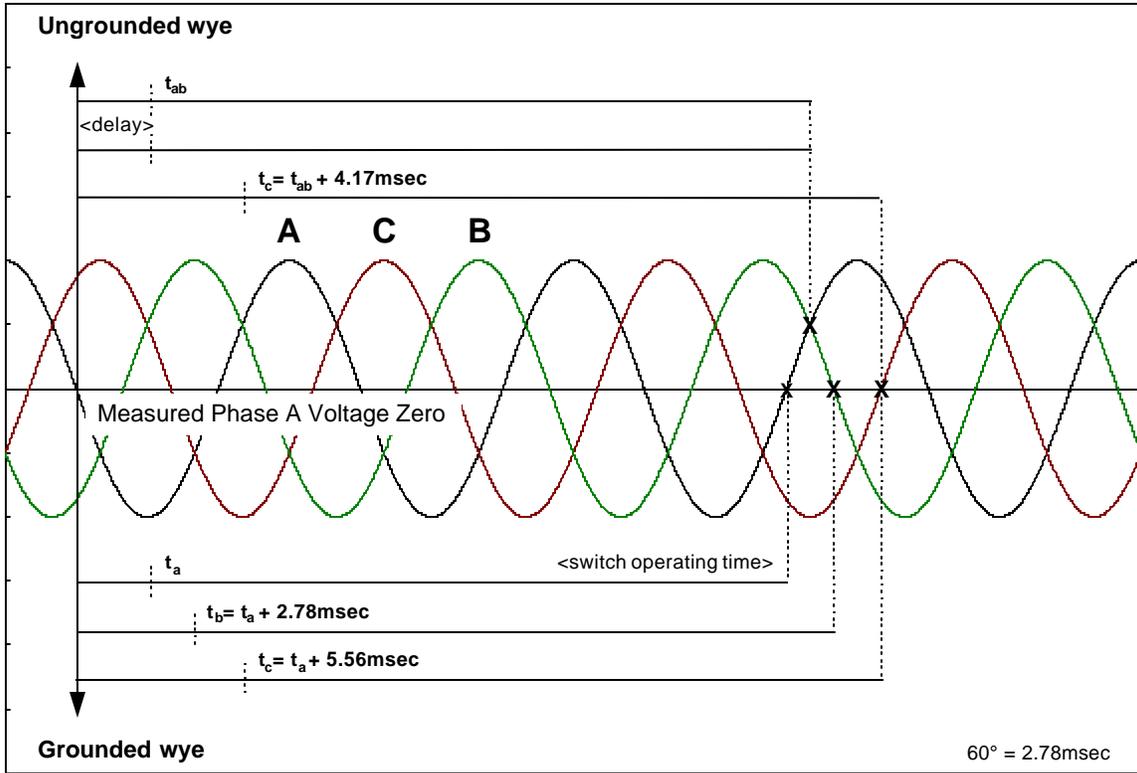


Figure 3: Concept of Synchronous Closing Control

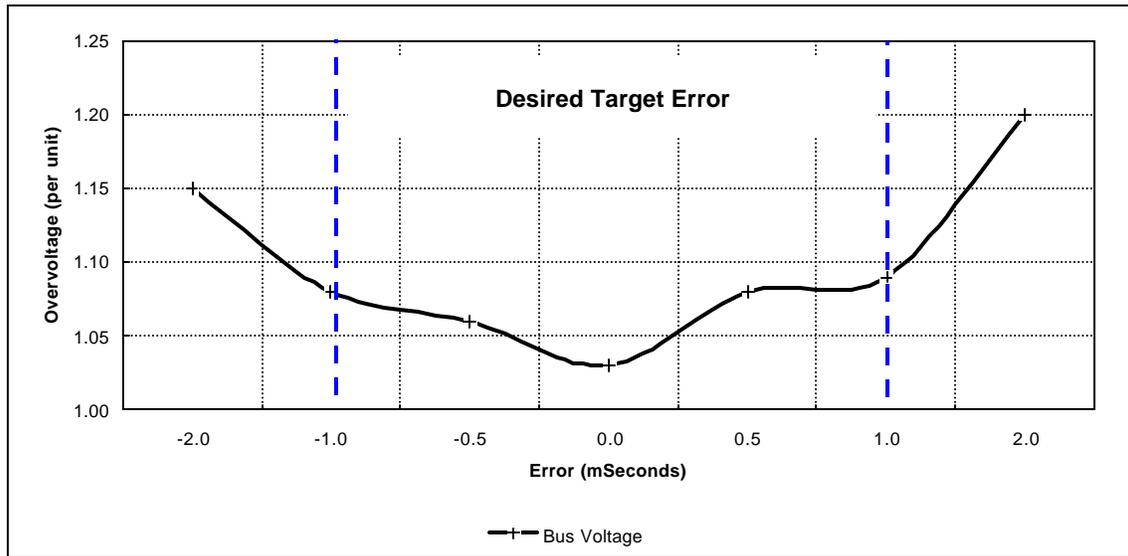


Figure 4: Example Transient Overvoltage Level vs. Timing Error

Pre-Insertion Device

A pre-insertion impedance (illustrated in Figure 5) provides a means for reducing the transient currents and voltages associated with the energization of a shunt capacitor bank. The impedance is "shorted-out" (bypassed) shortly after the initial transient dissipates, thereby producing a second transient event. The insertion transient typically lasts for less than one cycle of the system frequency. The performance of pre-insertion impedance is evaluated using both the insertion and bypass transient magnitudes, as well as the capability to dissipate the energy associated with the event, and repeat the event on a regular basis. The optimum resistor value for controlling capacitor-energizing transients depends primarily on the capacitor size and the source strength.

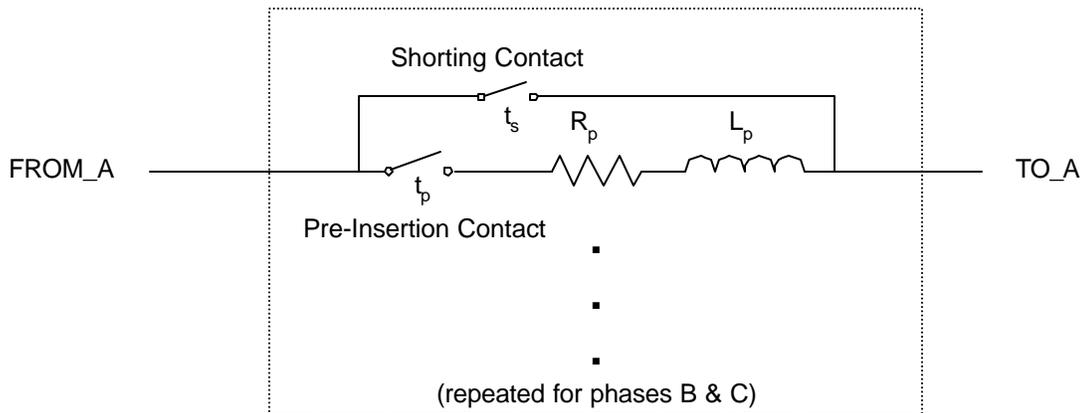


Figure 5: Component Configuration for Pre-Insertion Switching

Fixed Inductors

Fixed inductors have been used successfully to limit inrush currents during back-to-back switching. Typically, the value of these inductors is on the order of several hundred microhenries. In addition, inductors provided for outrush current control may be applied, and are typically 0.5 - 2.0 millihenries. Previous research indicates that these fixed reactors do not provide any appreciable transient overvoltage reduction.

MOV Arresters

Metal oxide varistors (MOVs) can limit the transient voltages to the arrester's protective level (maximum switching surge protective level, typically 1.8 - 2.5 per-unit) at the point of application. The primary concern associated with MOV application is the energy duty during a restrike event. Although a rare occurrence, a switch restrike generally results in the highest arrester duty for arresters located at the switched capacitor. In addition, remote arresters (including low voltage customer applications) may be subjected to severe energy duties if voltage magnification occurs.

Back-to-Back Capacitor Switching

Energizing a shunt capacitor bank with an adjacent capacitor bank already in service is known as “back-to-back” switching. High magnitude and frequency currents, illustrated in Figure 6, will flow between the banks when the second bank is energized. This current must be limited to acceptable levels for switching devices and current transformer burdens. Generally, series reactors are used with each bank to limit the current magnitude and frequency, although pre-insertion resistors/inductors may be used with some types of switches. The frequency and magnitude of the inrush current during back-to-back switching depends upon the size of the discharging capacitor bank, the impedance of the discharging loop, and the instantaneous capacitor bank terminal voltage at the time of contact closure. The impedance of the discharging loop is determined by the inductance between the banks rather than the system inductance (L_s). The magnitude of the inrush current is therefore much higher than for the isolated bank energization (I_{pk}). Typically, the inrush current lasts for only a fraction a power frequency cycle. This high-frequency inrush current may exceed the transient frequency momentary capability of the switching device (e.g. ANSI C37.06) as well as the I^2t withstand of the capacitor fuses. It may also cause false operation of protective relays and excessive voltages for current transformers (CTs) in the neutral or phase of grounded-wye capacitor banks. The current must be evaluated with respect to the transient frequency momentary capability (close and latch) rating of the switch, as well as the I^2t withstand of the capacitor fuses. Switch manufacturers should be consulted for the appropriate current (I_{pk}) and frequency (f) ratings of the device. Connecting the two neutral points together and grounding may control high frequency substation ground mat currents with a single connection to the grid.

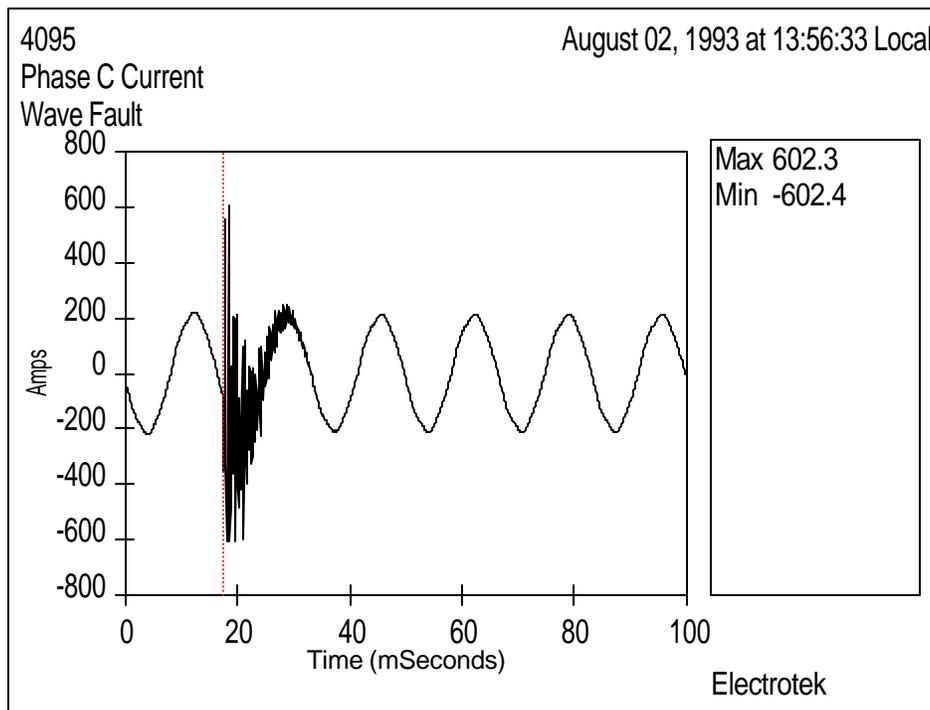


Figure 6: Feeder Current During Back-to-Back Switching

- a) Solutions to excessive inrush currents usually involves:
- b) Adding current-limiting reactors to decrease the peak current and frequency of the oscillatory inrush current.
- c) Adding pre-insertion resistors or inductors to the switching device.
- d) Adding synchronous closing control to the switching device.
- e) Selecting component ratings (e.g. breaker, CT burdens, etc.) to withstand the inrush current characteristics.

Capacitor Bank Restrike Events

A capacitor-switching device de-energizes a capacitor bank at a current zero (illustrated in Figure 7). Since the current is capacitive, the voltage at the time of current interruption is at a system peak. Successful interruption depends on whether the switch can develop sufficient dielectric strength to withstand the rate of rise and the peak recovery voltage. For a grounded-wye capacitor bank, two times (2.0 per-unit) the system peak voltage will appear across the switch contacts one-half cycle after interruption. If the switch cannot withstand this recovery voltage, the switch will restrike.

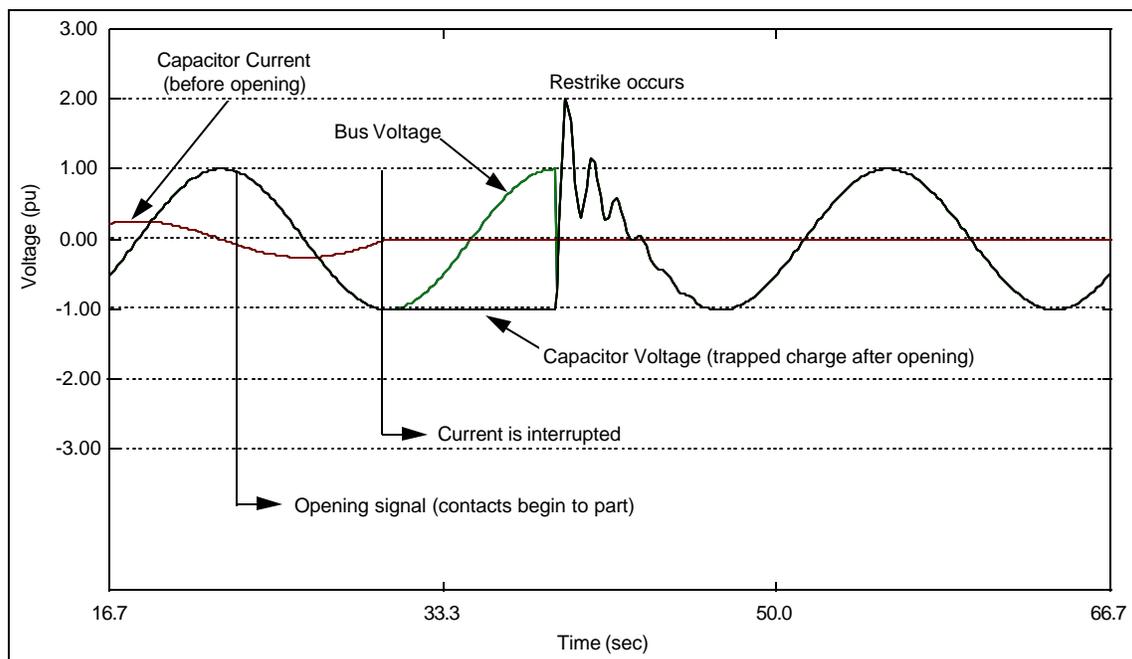


Figure 7: Illustration of Capacitor Bank Restrike Event

During normal grounded-wye capacitor bank de-energization, the capacitor current is interrupted at the peak system voltage thus leaving a 1.0 per-unit trapped charge on the capacitor. This trapped charge results in an offset in the transient recovery voltage (TRV) that reaches a magnitude of 2.0 per-unit one-half cycle after opening. Significant transient voltages can occur if the switch restrikes during clearing. The worst restrike transient occurs when twice the system peak voltage appears across the switch contacts. Theoretically, in this case, the magnitude of the transient voltage approaches 3.0 per-unit. Ungrounded-wye capacitor banks may expose the capacitor switch to recovery voltages

greater than 2.0 per-unit. Recovery voltages may reach 2.5 per-unit on the first phase to open when the other phases open at the next current zero. If two of the phases delay opening, the recovery voltage may reach 3.0 per-unit on the first phase to open. Finally, if one of the other phases delays, the transient recovery voltage would be 4.1 per-unit. If a restrike occurs on the first phase to open at 2.5 per-unit, a recovery voltage of 6.4 per-unit can occur on one of the other two phases because of the voltage that builds up across the neutral capacitance. The high recovery voltage on another phase can cause a second restrike, resulting in a two-phase restrike.

Capacitor switch restrike events may produce high voltage surges that result in severe energy duty for adjacent arresters or damage for unprotected equipment. Therefore, it is desirable to select a switching device that will minimize the possibility of a restrike event. In addition, it is advisable to protect adjacent equipment with appropriately sized arresters.

The energy duty requirements for arresters at capacitor bank locations depend on the size of the capacitor and on existing arresters located at the substation. In general, the most severe duty for an arrester near a capacitor bank occurs during a switch restrike. This is due to the trapped charge on the capacitor at the instant the restrike occurs, and results in a greater magnitude of the voltage oscillation.

It is also important to consider the coordination of MOV arresters (at the capacitor location) with any conventional gapped type arresters in the substation. It is important that the protective level of the MOV arresters be low enough to prevent operation of the gapped arresters. This is often difficult to achieve. If coordination is not possible, there are three options for arrester protection at the substation involved:

1. Replace all of the gapped type arresters in the substation with MOV arresters. The arresters will share the energy duty in the event of a restrike and there should be no danger of arrester failure.
2. Add one set of MOV arresters. This will greatly decrease the probability that a conventional arrester will fail during a capacitor restrike event because the MOV arrester will reduce the chance of a conventional arrester sparkover. The minimum size MOV should be used for best coordination with existing arresters.
3. Use only conventional gapped type arresters at the substation. This option relies on the integrity of the capacitor switch to prevent a restrike event. If a restrike would occur, it is unlikely the conventional arresters would be able to withstand the associated energy duty.

Power Quality Concerns During Capacitor Switching

Power quality symptoms related to distribution capacitor switching include: customer equipment damage or failure (due to excessive overvoltage), adjustable-speed drive or other process equipment shutdown (due to dc bus overvoltage), TVSS failure, and computer network problems. Two specific concerns addressed in the following sections include:

1. Magnification of capacitor switching transients
2. Nuisance tripping of end-use equipment (adjustable-speed drives).

These concerns have become particularly important as utilities institute higher power factor penalties, thereby encouraging customers to install power factor correction capacitors. In addition, nontraditional customer loads, such as adjustable-speed drives, are being applied in increasing numbers due to the improved efficiencies and flexibility that can be achieved. This type of load can be very sensitive to the transient voltages produced during capacitor switching.

Voltage Magnification During Capacitor Switching

Voltage magnification occurs when the transient oscillation, initiated by the energization of a utility capacitor bank, excites a series resonance formed by the low voltage system. The result is a higher overvoltage at the low voltage bus. Previous analysis has indicated that the worst magnified transient occurs when the following conditions are met:

1. The size of the switched capacitor bank is significantly larger (>10) than the low voltage power factor correction bank (i.e. C_2 vs. C_4 - refer to Figure 8).
2. The energizing frequency (i.e. f_2) is close to the series resonant frequency formed by the step-down transformer and the power factor correction capacitor bank (f_4) (refer to following equations).
3. There is relatively little damping (resistive) provided by the low voltage load (typical industrial plant configuration - primarily motor load).

Previous computer simulations and in-plant measurements (example shown in Figure 9) have indicated that magnified transients between 2.0 and 4.0 per-unit are possible over a wide range of low voltage capacitor sizes. Typically, the transient overvoltages will simply damage low-energy protective devices (MOVs) or cause a nuisance trip of a power electronic device. Important system variables to consider when analyzing this phenomenon include:

- Switched capacitor bank size / lower voltage capacitor bank size and location
- System loading / transformer characteristics
- Circuit breaker characteristics (closing resistors/inductors, closing control, etc.).
- Arrester size(s), rating(s), and location(s)

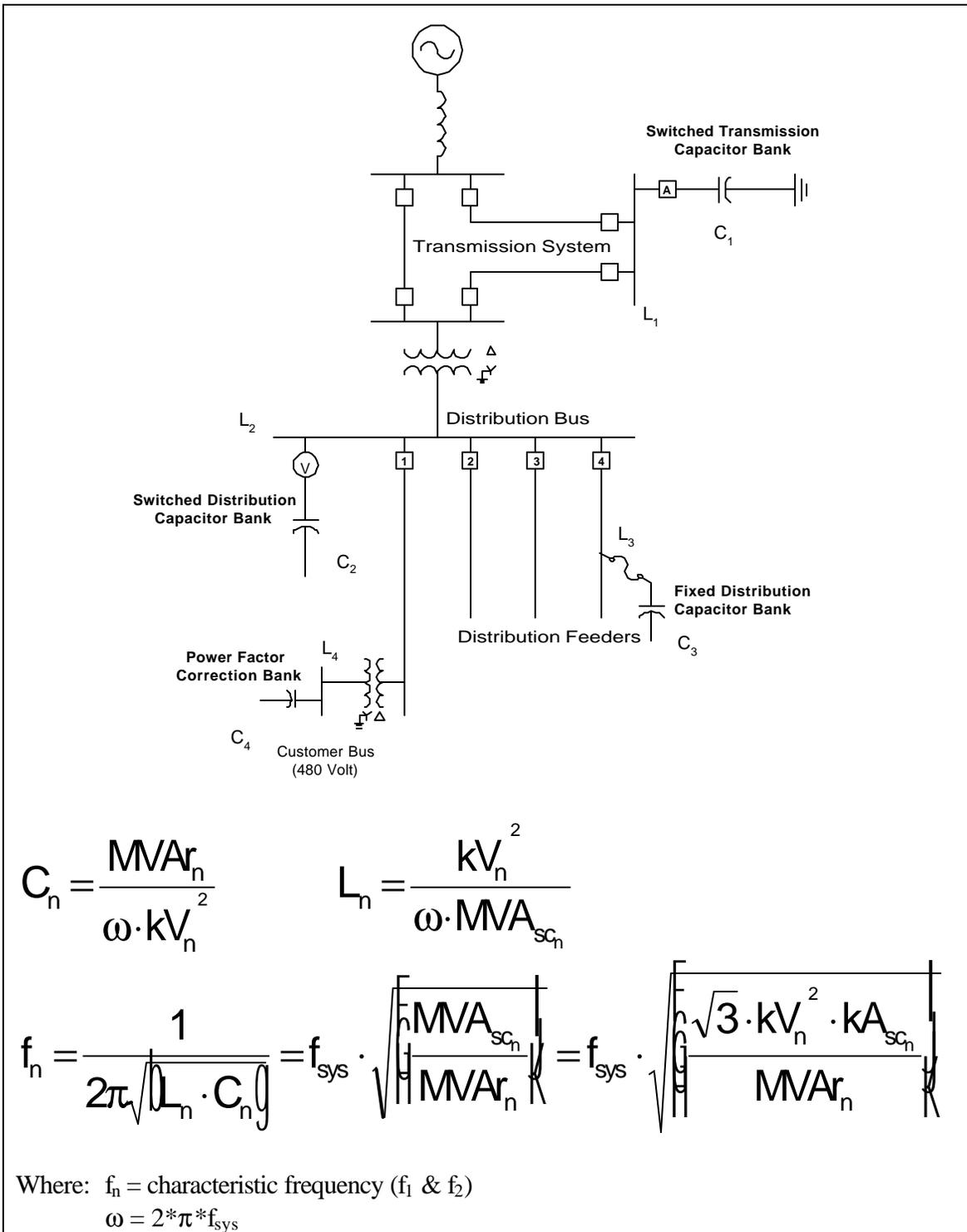


Figure 8: Circuit for Evaluating Voltage Magnification

Figure 9 illustrates an example-simulated capacitor energizing transient and the resulting transient voltage at the lower voltage customer power factor correction capacitor bank.

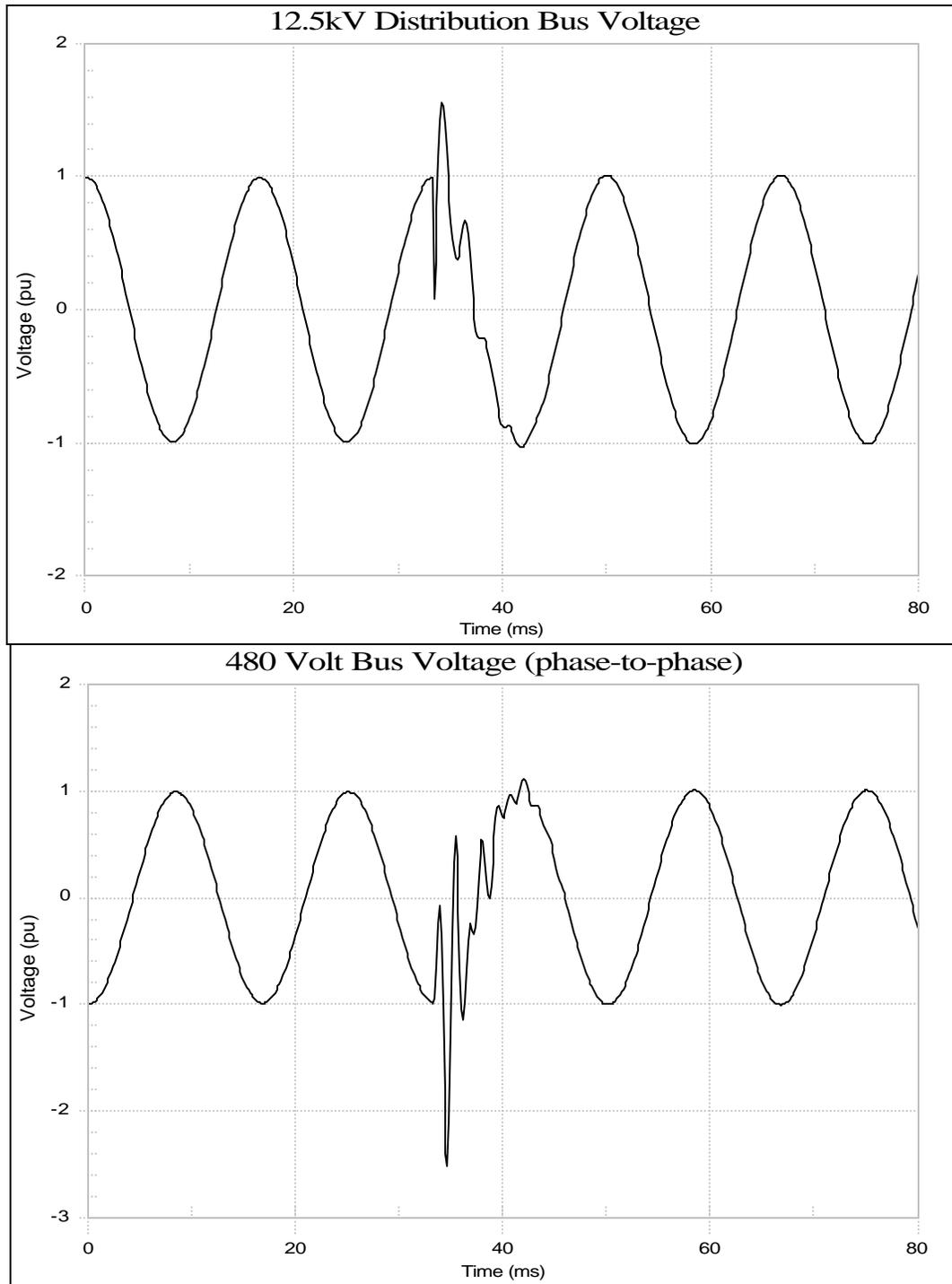


Figure 9: Voltage Magnification during Capacitor Switching

Solutions to the voltage magnification usually involve:

- a) Detuning the circuit by changing capacitor bank sizes, moving banks, and/or removing banks from service.
- b) Switching large banks in more than one section.
- c) Using one of the previously described overvoltage control methods (pre-insertion resistor/inductor or synchronous closing control).
- d) Applying surge arresters (MOVs) at the remote location
- e) Converting low voltage power factor correction banks into harmonic filters (detuning the circuit).

Nuisance Tripping of Adjustable-Speed Drives

Nuisance tripping refers to the undesired shutdown of an adjustable-speed drive (or other power-electronic-based process device) due to the transient overvoltage on the device's dc bus. Very often, this overvoltage is caused by transmission and/or distribution capacitor bank energization. Considering the fact that many distribution banks are time clock controlled, it is easy to see how this event can occur on a regular basis, thereby causing numerous process interruptions for the customer.

An adjustable-speed drive system consists of three basic components and a control system as illustrated in Figure 10. The rectifier converts the three-phase ac input to a dc voltage, and an inverter circuit utilizes the dc signal to produce a variable magnitude, variable frequency ac voltage, that is used to control the speed of an ac motor. A dc motor drive differs from this configuration in that the rectifier is used to control the motor directly.

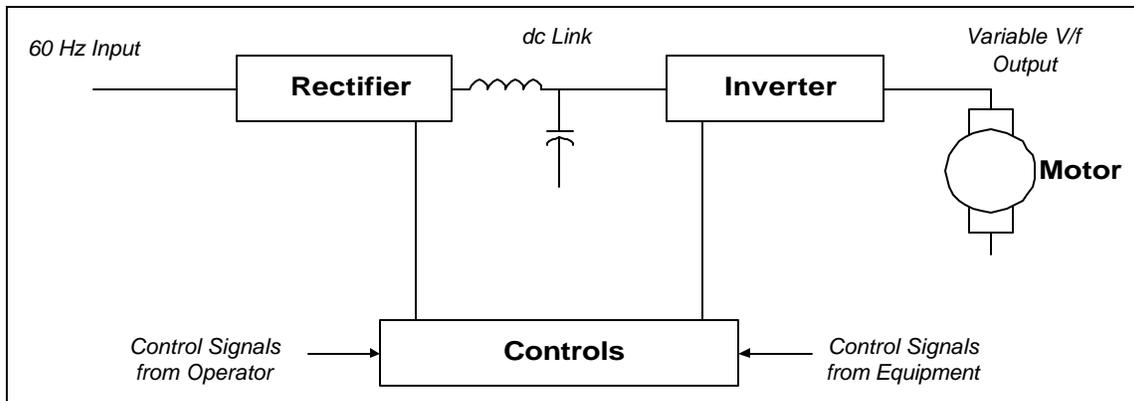


Figure 10: Circuit Illustrating ASD Components

The nuisance-tripping event consists of an overvoltage trip due to a dc bus overvoltage on voltage-source inverter drives (i.e. pulse-width modulated - PWM). Typically, for the protection of the dc capacitor and inverter components, the dc bus voltage is monitored and the drive tripped when it exceeds a preset level. This level is typically around 780 volts (for 480 V applications), which is only 120% of the nominal dc voltage. The potential for nuisance tripping is primarily dependent on the switched capacitor bank size, overvoltage controls for the switched bank, the dc bus capacitor size, and the inductance between the two capacitors. It is important to note that nuisance tripping can occur even if the customer does not have power factor correction capacitors.

The most effective methods for eliminating nuisance tripping are to significantly reduce the energizing transient overvoltage, or to “isolate” the drives from the power system with series inductors, often referred to as “chokes”. The additional series inductance of the choke will reduce the transient magnitude at the input to the ASD and the associated current surge into the dc link filter capacitor, thereby limiting the dc overvoltage.

While determining the precise inductor size for a particular application may require a detailed computer simulation study, a more common approach involves the widespread application of a standard “3%” value. The 3% size is based upon the drive kVA rating and is usually sufficient for most applications where voltage magnification isn’t also a concern. Figure 11 illustrates an example (simulation) dc overvoltage transient before and after the application of a 3% ac choke.

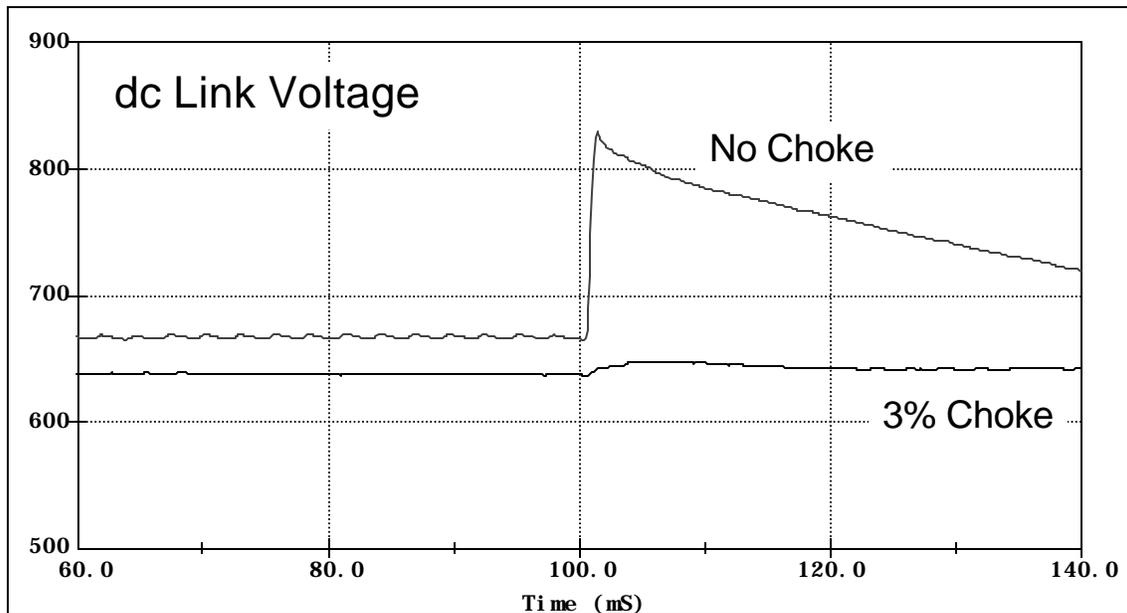


Figure 11: Illustration of Impact of ac Choke on dc Overvoltage Level

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