Edward L. Owen

A History of Harmonics in Power Systems

We operating men, I think, all agree that we have harmonics. I think we all agree that, like the poor, the harmonics will always be with us. If we could get rid of them, we would be very glad to do so.

—*J.B. Fisken (Sept. 8, 1916)*

In 1893, engineers were grappling with a motor heating problem at Hartford, Conn. To identify its cause and resolve the problem, those engineers conducted harmonic analyses of various electric waveforms throughout the power system to which the motor was connected. Alternating-current systems technology was new in 1893, and this was the first time, at least to the author's knowledge, an electrical applications problem was addressed using harmonic analysis as a tool. Ultimately, the source of motor heating was traced to transmission line resonance. This finding initiated widespread concerns for such resonances among the engineering fraternity. Three years prior, electricians at Portland, Ore., had struggled with a different type of transmission line problem, possibly due to harmonic components of line frequency. No evidence is known to exist that suggests these electricians ever considered using harmonic analysis. During this same time period, electrical manufacturers in Europe were not confronted by transmission line resonance because they did not use high-frequency (125, 133, or 140 Hz) for their alternating-current power transmission systems. This problem was uniquely American.

Problems associated with harmonic components of voltage and/or current waveforms have tormented power system engineers since the very beginning of the electric power industry. In the early days, the causes of their anguish often went unrecognized. Through the decades, harmonics have often been cited as the source for a great variety of problems, although the form in which the harmonics are manifest and with which they are resolved continually changes.

There is a certain fashionability about harmonics. Each time a new manifestation of the subject appears, it brings in a new era, with new symptoms, new views on allowable limits, new methods by which to measure, and more debate about all of these matters. Although outward forms may change, the underlying fundamental principles remain unaltered. By looking at historic patterns in which engineers recognize and approach harmonic issues, perhaps we can better anticipate developments in the future.

Frederick Bedell published a history of ac waveform in 1942 [1]. As one of the pioneers himself, he was eminently qualified for this task. His account is rather conventional, beginning with William Stanley in 1886. American engineers often identify William Stanley as the originator of alternating-current systems, although any claim of priority on behalf of Stanley needs to be properly qualified and should be restricted to North American experience. It is important to realize that many others also made important contributions, both in America and the rest of the world.

Bedell entered the field of alternating current in 1890 and immediately became interested in the effect of waveform. Having begun at that early date, he is certainly a pioneer, and it is reasonable to expect he would have firsthand knowledge of most important developments. Still, his account does seem to have gaps. This story builds on Bedell's and does not repeat many items in his version. Some missing milestones are:

- 1888—Tesla published his work on polyphase systems.
- 1889—Steinmetz came to America and began working for Rudolph Eickemeyer in Yonkers.
- 1890—First long-distance electric power transmission system was installed at Portland, Ore. (12 miles and 133 Hz).
- 1893—Steinmetz came to work for Thomson-Houston in Lynn, Mass., and was immediately put to work, solving a serious harmonics problem at Hartford, Conn.

The work at Hartford probably initiated widespread concerns for transmission line resonance as a problem. Their experience at Hartford also caused General Electric to stop further efforts in promoting high frequency for power systems. It is clear there were concerns for transmission line resonance, but we are left to speculate on exactly how these concerns arose.

Transmission Line Resonance

Around the turn of the century, the open literature contains several references to transmission line resonance as a potential problem, without explaining how or why this concern came about [2, 3]. While conducting research for his book on Steinmetz, Ron Kline discovered some information suggesting that Steinmetz was involved in addressing such problems [4].

If one accepts that indeed there was a "problem" in those early days and looks for more details to that effect, a pattern slowly emerges. It is a little like watching a baseball game through a knothole in the fence—kind of hard to get "the big picture." However, additional information not available in the open literature can be found in various archives. In some cases, personal papers of some of our predecessors are preserved and made available for research. Through their written accounts, we can open up the

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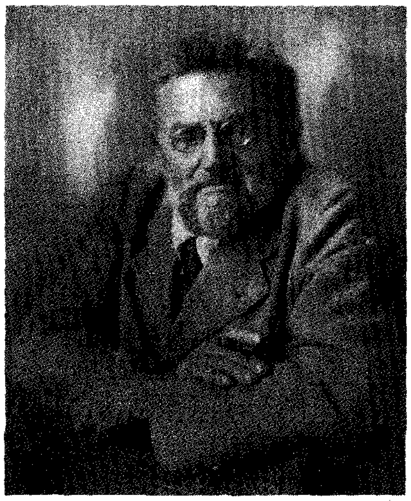
knothole a bit. Charles Proteus Steinmetz was one such personality, involved in early power transmission systems and whose papers are available for research [5]. William Stanley was also a pioneer, involved in early high-voltage power transmission, and his papers are likewise available for research [6].

Most modern power engineers immediately reject any idea that transmission line resonance could play a significant role in these early problems. They do so on the basis that power frequency resonance does not occur in transmission lines that are only 10 to 15 miles long. They fail to consider what would happen if the nominal power system frequency were 125 or 133 Hz rather than 50 or 60 Hz and the generator voltage waveform was rich in higher harmonics, rather than a good waveform like modern generators.

A high-voltage problem was observed at the General Electric motor installed in Hartford. This was thought to be due to resonance. Steinmetz proposed at least two solutions to overcome what proved to be harmonic resonance at Hartford. The first was to reduce the system frequency to one-half of its original value. That is, reduce the original frequency value of 125 Hz to a new value of 62.5 Hz. The second option was to restack iron laminations in the motor, to withstand the higher operating voltage. Keep in mind, both motor and generator were tested in the factory before shipment, where they worked fine. The difference between motor conditions at the factory and at the site was the 10-mile transmission line.



Charles Proteus Steinmetz. (Schenectady County Historical Society—printed with permission.)

The Hartford installation is described in a book by Glenn Weaver [7]. Hartford Electric Light Company built a hydroelectric plant at Rainbow Falls on the Farmington River in 1890. For several years, the plant was more an electrical laboratory than an operating plant. Most of the changes at Rainbow plant were made at relatively slight cost to Hartford Electric Light because A.C. Dunham was able to convince the Thomson-Houston Company of the value of the plant for experimental purposes. Since it was experimental, many well-known engineers are known to have visited the plant.

In 1892, the Thomson-Houston organization combined with Edison General Electric to form General Electric Company. This was the new GE that Steinmetz came to work for in January 1893 and which provided the 300 KW, 125 cycle, 3-phase generator to upgrade the Rainbow plant. Power generated at Rainbow Falls was transmitted to downtown Hartford where it drove a

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synchronous motor that in turn drove dc generators for street railways.

Steinmetz knew of the possibility of harmonic resonance and made supporting calculations, as he tested his theory against measured quantities. Journal entries are inscribed in his own handwriting, headed "Farmington River Line" [5]. One page in his journal, dated May 18, 1893, contains the following among other specific entries:

- nominal voltage—3.8 KV
- system frequency—125 Hz
- line length—10.13 miles
- conductor #4 copper, spaced 14 inches apart.

He calculated total loop inductance and compared this to a measured value. He also calculated line capacitance or charging current. Using line inductance and capacitance parameters, probably with load inductance, he calculated that the line became resonant around 1,600 Hz or the 13th harmonic of line fundamental frequency (125 Hz). Both the generator installed at Rainbow Falls and the motor located in downtown Hartford have potential (voltage) waveforms with substantial amounts of harmonic components. When engineers speak of the parameter *potential* with units of *volts*, it is confusing. The British speak of pressure and the French speak of tension.

The most marvelous aspect of this glimpse into history is an appreciation for how much they accomplished, in spite of working with very primitive tools and instruments. They did not have available to them modern instruments like oscilloscopes or spectrum analyzers. In 1893, they did not even have access to a good voltmeter.

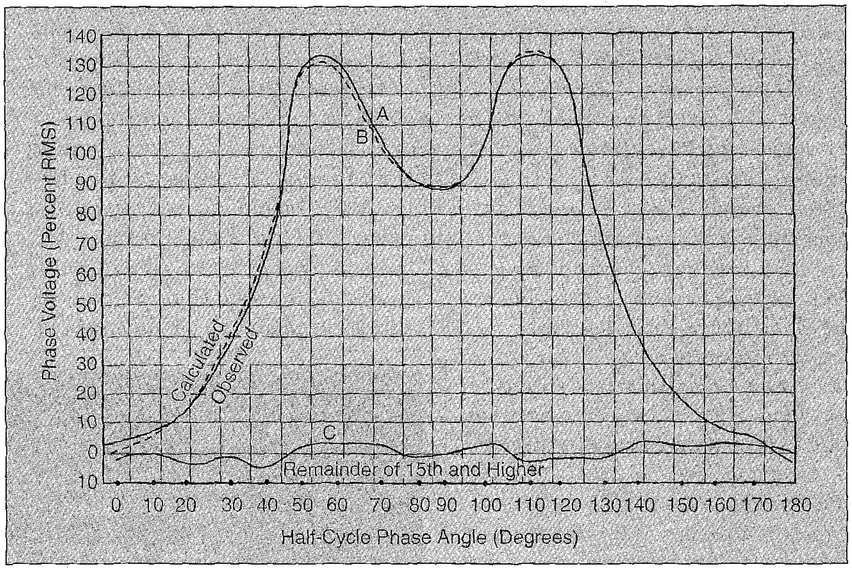

Fig. 1. No-load E.M.F. of Type AT alternator. (Source: [10].)

Oscillographs were not yet available, and wave forms were generated on a point-by-point basis by a contact-making device called a wave meter. In 1890, the wave meter was available and in use at both GE and Westinghouse factories. The detector of the wave meter used a "null galvonometer" rather than a "deflection galvonometer" (a.k.a. voltmeter), meaning they had to balance a bridge each time they took a data point. Yet they were able to construct electrical wave forms and conduct Fourier analyses. Steinmetz brought with him to GE the mathematical background to conduct harmonic analysis on time-based waveforms produced by the wave meter. Reportedly, it took him about one hour to produce each coefficient of the Fourier analysis. The *method of selected ordinates* had not yet been invented. Look at the data points in Fig. 1—they are not uniformly spaced. Steinmetz calculated Fourier coefficients for the potential waveforms through the 15th order. Amazingly, with 36 data points per cycle of the 125 Hz fundamental frequency, the commutator of the wave meter was effectively generating a "strobe pulse," to capture another data sample, 4,500 times per second. Why should we be amazed? These are some of the same people who, later in 1910, along with new recruits like Alexanderson, produced radio-frequency broadcast waveforms of 100,000 Hz from rotating machines.

Willamette Falls Transmission Line

The following anecdote was discovered in the archives of the Oregon History Center during a visit in July 1988 [8, 9]. This account is paraphrased somewhat and substantially condensed to fit available space.

In 1890, PGE (Portland General Electric) proposed to install hydrogenerators on the Willamette river to provide lighting service in downtown Portland. From previous experience, they felt a need to operate the transmission line at a nominal potential of 4,000 volts, this to cover the 12-mile distance from Willamette Falls to downtown Portland. PGE inquired of Westinghouse Electric for a proposal and tender offer for the generators. Westinghouse refused to build generators rated at such a high potential. At that time, standard voltage ratings for ac generators were 1,200, 2,400, and 3,600 volts. Standard potential ratings for transformers were 1,000, 2,000, and 3,000 volts, allowing 20 percent drop in potential between

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source and load. Insulation systems rated 4,800 volts had not been developed for generators. Sensing their disappointment, Scott and others at Westinghouse suggested PGE might wish to discuss their situation with William Stanley. Stanley was then conducting some experimental research on *high-voltage transmission* at his laboratory in Great Barrington, Mass. During their visit, Stanley told them his research showed the system could be built at 4,000 volts, and that they should proceed. With this encouragement, PGE engineers went back to Westinghouse asking them to reconsider. Westinghouse did and agreed to provide the alternators but to do so without a warranty. PGE agreed to the terms and the equipment was built and installed. The record says, there was a *high point* (approximately 500 feet higher than the balance of the line) along the transmission line. During operation, insulators kept flashing over at that *weak point.* PGE placed a pile of dirt at that location and stationed a man there with a shovel during operating hours (the transmission system only operated for a few hours in the evening to provide light). When the insulators did flash over, it was the job of the man with a shovel to throw dirt on the insulators and put out the arc. They thought it worked just fine!

When I first read this story, I thought it illustrated an important point, in a marvelous way. That point is *attitude* and it means, if you want something to work you can probably overcome almost any obstacle. Sometimes it is also called "work-around," where you work around the problem. Now, in retrospect, considering the experience at Hartford and the similarity of the two installations, Portland probably had a harmonic resonance problem also. The so called "high point" on the transmission system was not that much higher than the rest of the line. It does not make sense that a small increase in elevation would make any difference in dielectric capability or cause any significant weakness in the line insulation and support. Westinghouse alternators of that day had a relatively poor waveform, similar to that of the GE machines. Therefore, they would also have high harmonic content of their voltage wave forms. Harmonic resonance of the line provides a more likely explanation for flashover of the line insulators than high elevation.

Alternator Designs

In 1895, both GE and Westinghouse introduced new generator designs using distributed armature windings to substantially improve the waveform and making it more sinusoidal. In 1896, an article in Electrical World describes both types of machines, as produced by GE [10]. The older type AT machine is specifically described as "limited to transmission line lengths of 5 to 10 miles, because of wave shape." Later in the article, the author reiterates its unsuitability for long transmission lines due to possible resonances. The newer type AP machine is described as producing "more nearly sine-waves." Engineers have worked hard to achieve machine designs that produce sinusoidal wave forms.

Generators Operating in Parallel

The next harmonics problem to appear in the literature also involved generator waveform. Problems were reported with excessive neutral current when generators were solidly grounded and operated in parallel. Today, this is a familiar problem involving zero-sequence third-harmonic voltage in wye connected machines. This problem was then and now is also solved by careful control of the armature winding pitch factor to nearly eliminate troublesome third harmonic voltages, when the machine neutral is to be solidly grounded [11].

Telephone Interference Factor

The third problem to appear in the literature was referred to as inductive coordination or, more commonly, TIF (Telephone Interference Factor). This new "harmonic problem" in 1910 resulted in a long process of trial and error exploration to find suitable wave form standards [12]. Many waveform-based factors were introduced, some of which survived in technical standards until the 1980s (e.g., distortion factor, deviation factor, etc.). TIF was given even greater impetus when mercury arc rectifiers came into more general use and were applied at larger ratings [13].

Shunt Capacitors and Filter Banks

Shunt capacitors have been used to improve power factor in electrical systems at least since the time of William Stanley. In 1960, there were large numbers industrial power systems with many individual shunt capacitors installed on industrial power systems, all without much concern for harmonic resonance. Today, many of those shunt capacitors are equipped with a series reactor, making them into tuned filter banks. Most engineers in active practice today remember a time in the 1960s when it was that way, and they think it has always been that way. They view the recent introduction of static drives with their switching characteristics and associated harmonics as "paradise lost." They search for some magic elixir that will produce paradise regained. There are now two mostly competing concepts of proper power system design regarding application of filter banks for power factor improvement—central and distributed supply. The central supply concept holds that there has to be some overall agent (e.g., central utility) in the network that corrects net power factor for all loads connected to the bus, e.g., "do it one time." The filter bank design is on the basis of using block switching of individual units and progressive tuning to 5th, 7th, 11th, and 13th harmonics, but done once per bus. The distributed supply concept holds the opposite—each load on the bus will provide its own correction, and the role of the central utility is diminished.

Harmonic Analysis

As part of his researches into the conduction of heat in 1812, French mathematician Jean Fourier developed a mathematical artifice for evaluating complex functions. His method of *Fourier analysis* expands the complex function into a series of sine and cosine functions. *Harmonic analysis* is the name given by Thomson and Tait to a method first used in mathematical physics and later used by Bernouilli and Euler in the middle of the 18th century. Maxwell applied it to physical problems where the actual complex state is regarded as the superposition of a number of simpler states that can coexist without interfering with each other. Steinmetz was familiar with these methods and brought them with him to Lynn.

In 1904, Silvanius Thompson introduced the *method of selected ordinates* as a way to expedite manual calculation of

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Fourier coefficients from a time series [14]. Reportedly, this method decreased the time required to perform a harmonic analysis by a factor of ten to one. In retrospect, it is hard to believe calculation of Fourier coefficients was ever done any other way than by using selected ordinates, where the data points are spaced at regular intervals, like 15 degrees for 24 data points. In Fig. 1, note the marks along the abscissa which denote data points—they are not evenly spaced. No wonder it took an hour to calculate each coefficient!

In 1965, a similar productivity increase occurred when J.W. Cooley and J.W. Tukey introduced the Fast Fourier Transform (FFT) as a way to increase the speed with which a computer code can extract the discrete Fourier transform of a time series [15]. Incidentally, Tukey also devised the "Students T Test" used in statistical work. The FFT is a very familiar and useful engineering tool but is often misunderstood.

Changing Times

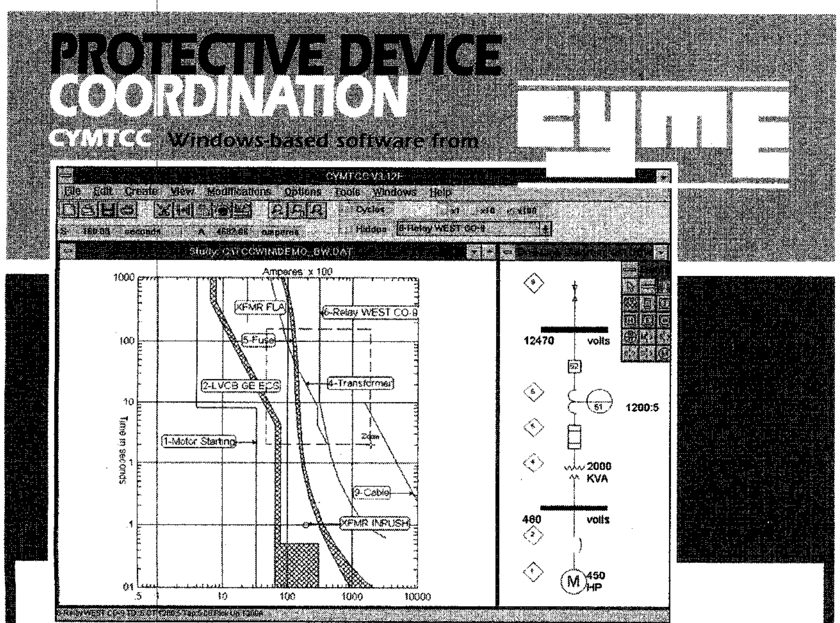
Transmission line resonance appeared as a topic in the AIEE Transactions several times prior to the turn of the century. The first time the word *harmonics* appears in the title of a paper is 1933. In 1913, the subject was also presented to the British Institution of Electrical Engineers. In his inaugural address, William Duddell discussed pressure (voltage) rises and identified transmission line resonance as one of three such causes [3]. He specifically pointed out that higher harmonics was often an unexpected cause of transmission line resonance. This is not surprising considering the role played by Henry Hobart as an intellectual link between engineers in America and Europe around the turn of the century. Specifically, Hobart worked at Thomson-Houston in Lynn until 1891, when he moved to London and entered into education and private practice. Those citations in the Engineering Index with the initials HMH at the end are by Henry M. Hobart.

One way to appreciate how times have changed is to consult various indexes published by the AIEE/IEEE. During the first 25 years, the Index to Transactions of the AIEE had two ways of classifying citations; paper index and topical index. For the years 1884 to 1900, seven papers are listed under the topic of harmonics. For the years 1901 to 1910, it lists 12 papers on harmonics. In 1911, the format of the index changed, listing subjects and authors. However, for the years 1911 to 1921, harmonics was not listed as one of those subjects. Instead, you would look under waveform. The topic of harmonics returned to the index in the period 1922 to 1938 with 13 entries. For the decades beyond, the number of citations slowly increased each period, with 18 entries for the decade 1950 to 1959. What was a hot topic in 1895 was nearly invisible 15 years later, to return again in another 15 years.

In 1925, harmonic analysis was a formal procedure used by engineers to approach problems, but considered as a mathematical subject more so than engineering. Technical papers of that era focused on new problems, effects and phenomena with any description of methods used buried in an appendix at the end. Today, it is the other way around. Many papers are written which only describe a new method of solving an old problem.

Deja Vu All Over Again

Within the past three years, the engineering literature is full of articles on over-voltage and reflected waves associated with pulse width modulated (PWM) drives employing insulated gate bipolar transistor (IGBT) switching elements. The current situation with IGBT drives is comparable to that facing Steinmetz in 1893. To list some of the differences. In 1893, there were no oscilloscopes or spectral analyzers, critical distances between power supply and motor were measured in miles, not feet, and IGBT drives with PWM waveforms were unknown. Also, harmonic orders of interest then was 13, not 100, or more like today when PWM switch-



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ing frequencies are 5 KC or higher. Some things have changed.

Something Old, Something New

IEEE Standard 519 is currently the principal interface standard used by most engineers to arbitrate harmonic issues [16]. How good is IEEE 519? Are there areas where it is deficient? Is it time to revise the standard?

Advances in power electronics and recent developments in industrial applications have presented engineers with a new type of harmonic related phenomenon, something called "inter-harmonics." What are inter-harmonics? How are they measured? What are their effects? What are reasonable limits to avoid possible problems? Who is responsible for providing leadership? Can we learn anything from the past? Some answers can be found in IEC standards. Perhaps, some readers will write in with their experiences.

IEC standards are somewhat ahead of IEEE standards in dealing with inter-harmonics. IEC Technical Committee No. 77 has prepared a new series of standards under the banner IEC Standard 1000: electromagnetic compatibility (EMC) [17]. It consists of several parts, each focusing on specific aspects of the larger EMC topic. Therefore, IEC regards harmonics and inter-harmonics as subsets of a larger topic and not independent subjects. Are the new IEC standards adequate? Are there additional needs not addressed by the IEC standards? Can a study of history help with the new order?

IEC-1000-2-1 defines inter-harmonics as follows:

"*Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental.* They are not harmonics. They can appear as discrete frequencies or as a wide-band spectrum."

Experience has shown that inter-harmonics can cause equipment damage [18, 19]. Published papers provide rare insight into this subject, expanding awareness and knowledge of low-level harmonic related phenomena. Interestingly, a strict interpretation of the IEC definition of inter-harmonics produces an inconsistent result. The 65 Hz upper side-band resulting from 5 Hz amplitude modulation of 60 Hz power frequency fits the definition of an inter-harmonic spectral component while the 55 Hz lower side-bands do not fit the definition. This experience shows that amplitudes as small as 0.7% of rated current can affect equipment adversely. This is truly a threshold phenomena. Commercially available spectrum analyzers can just barely resolve spectral components at this level. They provide no margin for exploring cause-effect relationships. Special and expensive instruments are required.

Something Borrowed, Something Blue

Utility deregulation brings with it new challenges. Power contracts that once were negotiated in only a few hours' time and fit on one piece of paper may now require nearly a year to settle and consist of 30 pages. The contract may require that special instrumentation be installed at the Point of Common Coupling (PCC) to protect the world against power quality issues; such as simple harmonics or more elusive inter-harmonics. It may require that special equipment monitors be installed on exposed, critical machines or systems to protect against power quality issues from any source. These circumstances will surely create demands for new, more sophisticated instrumentation, new limits (usually lower but not always), and lots of discussion. All of this is occurring while utilities are reducing their technical staffs and aggressively marketing their services. These are exciting times. Are you prepared?

Conclusion

Wave forms of potential (voltage) and current in electric power systems are seldom the idealized functions on which engineering work is based. Harmonic analysis can be used to resolve complex time-based wave forms into spectral components. History teaches us that as new problems with harmonics arise, new instruments to measure the phenomenon will be offered and tighter limits on allowable deviations will probably be pushed. The old problems return to take on new forms.

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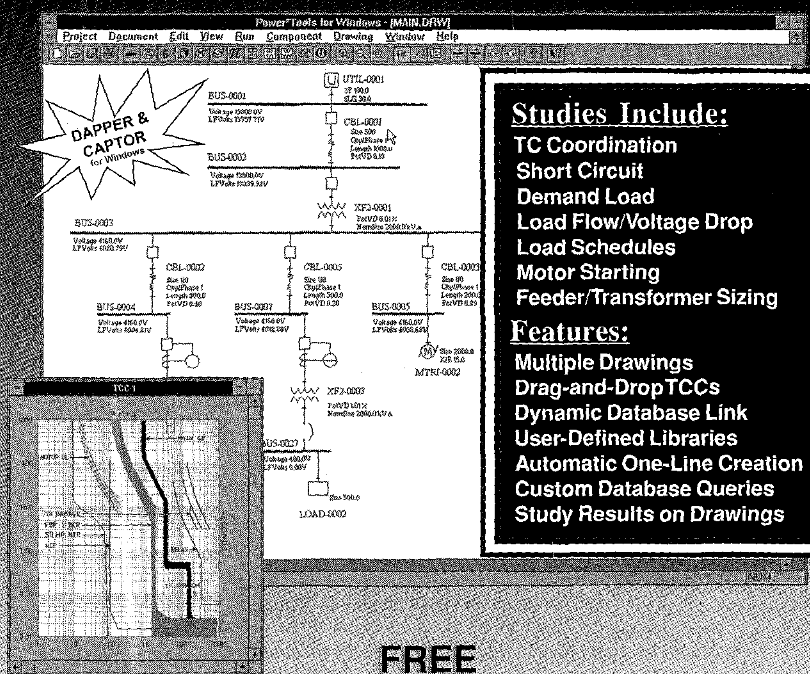

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