Gerhard Neidhöfer

50-Hz frequency

how the standard emerged from a European jumble

THE SO-CALLED "EUROPEAN" frequency of 50 Hz is one of the two standard frequencies that govern the electric power supply worldwide. As with 60 Hz, the "American" standard frequency, the history of 50 Hz is also specific and characterized by its own course of development from its first use up to final standards, involving various steps in between.

Typical for Europe was the short time it took to develop the first 50-Hz standards by fact and consensus by around 1900; but also typical was the slow promotion to regular national standards, which lasted until 1930–1950. When the European interconnected network was launched by three countries in 1958, 50 Hz became the heartbeat of a large grid system with considerable later extensions. In a worldwide context, the standard frequency of 50 Hz covers four and a half continents of the globe.

Frequency Measured in "Alternations" or "Cycles"

At the beginning of alternating current (ac) technology in the late 1880s, the term "frequency" was far from common. In the understanding of that era, an alternating current had simply a certain number of alternations. So the rate of a periodic oscillation was directly expressed by the number of alternations during a certain interval of time. As with the mechanical speed of rotation, the number of alternations of the current was also related to a minute. Thus, the early measure for the frequency was alternations per minute or reversals per minute. In the jargon of the day, the shortened term "alternations" was clear enough.

During the 1890s, more descriptive terms were suggested. In 1895, Silvanus P. Thompson, professor of physics at the London Technical College, wrote in one of his exemplary textbooks: "The number of periods accomplished in a second is called the *frequency* or *periodicity* of the alternations." He was ahead of his time because, in our modern terminology, the term frequency of an alternating current is used to express the number of oscillations during a defined interval of time. In the case of 50 Hz, the current oscillates 50 times a second, i.e., the current has 50 cycles/s. As a consequence, the early measure for a periodic oscillation leads to strange figures when converted to today's unit, such as

$$\frac{5{,}000 \text{ alternations/min}}{2 \text{ alternations/cycle}}$$

equals 2,500 cycles/min, and

$$\frac{2{,}500 \text{ cycles/min}}{60 \text{ s/min}}$$

equals 41 2/3 cycles/s, or 41.7 Hz.

The unit term hertz (Hz) used today to represent frequency in cycles per second is named after the physicist Heinrich Rudolf Hertz, renowned for having discovered fast electromagnetic radio waves.

Early Frequencies

133 or 125 Hz in North America

The history of electric utility frequencies began in 1886 in the United States, when the Westinghouse Electric Company (Westinghouse) built the first workable ac generating unit. The generator was belt driven, had a speed of 2,000 rev/min and eight magnetic poles, thus producing 2,000 × 8 = 16,000 pole reversals or current alternations per minute. The frequency, calculated as in the example above, was then

$$16{,}000 \text{ alternations/min}/(2 \times 60) = 133\ 1/3 \text{ cycles/s} \approx 133 \text{ Hz}.$$

The Thomson-Houston Company [later the General Electric Company (General Electric) after its merger with the Edison General Electric Company] preferred 15,000 alternations/min, corresponding to 1p25 cycles/s. Both frequencies were advantageously high to offer optimum conditions for electric lighting and for transformers to step down the transmission voltages to lower utilization levels.

For the safe design of direct-coupled prime movers and rotating alternating current/direct current (ac/dc) converters, however, such high frequencies were a serious obstacle. To allow operation with lower mechanical speeds and a reasonable number of magnetic poles, the frequency had to be dramatically reduced, as explained by the interrelationship:

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The electric utility world of our planet is governed by two frequencies, 60 Hz and 50 Hz, and is consequently divided into two incompatible electric spheres. While the 60-Hz frequency was selected as the standard in North America, 50 Hz became the favorite in Europe. These two distinct frequencies continued to spread around the globe until, today, the 60-Hz standard is found on one and a half continents (North America and part of South America) and in a few overseas countries, whereas four and a half continents (Europe, Asia, Africa, Australia, and the remaining part of South America) have adopted the 50-Hz standard frequency. A special case is Japan where the two standards are used in two separate parts of the country.

The historical background of the 60-Hz "American" standard frequency is generally well known. Much information about this complex matter was published in 1918 in *AIEE Transactions* by B.G. Lamme, in "a paper that covers only the story of American development" (quotation from the front page). This 60-Hz material was later summarized and updated by E.L. Owen in a history paper published in 1997 in *IEEE Industry Applications Magazine* and by P. Mixon in a survey paper from 1999 in *IEEE Power Engineering Review*. The "classic" 16²/₃ Hz, a distinct frequency used in electric rail traction, is also well covered in many papers. The history of the 50-Hz "European" utility frequency, however, was not well documented until 2008, when the Swiss Bulletin SEV/VSE published an article written by Prof. Dr. Gerhard Neidhöfer in German.

The present article, also authored by Gerhard Neidhöfer, has as its purpose the presentation of the main findings of his 2008 publication to an extended readership. This new version, written in English, provides an opportunity to better understand this complex matter and to learn from the author's continuing research in the field.

Even though this article focuses on the story of the "European" 50-Hz frequency, it occasionally explains contemporaneous 60-Hz events in North America, the continent that was the cradle of alternating current (ac) technology.

Gerhard Neidhöfer, born in Germany, earned the Dipl.-Ing. degree in electrical engineering from the Technische Hochschule, Darmstadt, Germany, and the doctor of science degree in applied mathematics from the Université de Grenoble, France. He joined Brown Boveri Company (BBC) in Baden, Switzerland, before graduation and enjoyed a 39-year career working there in the large generator and motor business. Since retiring in 1996 from Asea Brown Boveri (ABB), the successor to BBC, he has served as an expert consultant to the company and subsequently to ALSTOM, which took over the power generation business from ABB. He resides in Hausen bei Brugg, Switzerland.

Prof. Dr. Neidhöfer has lectured widely on various aspects of electric machines and has been a frequent contributor at international conferences. He has authored over 40 technical papers, coauthored two books on electric power engineering, and published in 2004 a highly regarded book covering the roots of three-phase ac technology and its promoters. In 2009, he gave a presentation on the technical and historical significance of the Rheinfelden hydroelectric generating station that, shortly after the completion of the Adams power station at Niagara Falls, became the first European large-scale hydroelectric power plant, a location from where, in 1898, the young three-phase ac technology and 50-Hz frequency began what became a world-wide expansion.

Gerhard has been an active IEEE Power & Energy Society member since 1984 and was named an IEEE Fellow in 1999 "for contributions to the development of electrical machines and to the international harmonization of electric machinery standards." In 2007, he authored his first history article published in this magazine, a concise but comprehensive summary of the early three-phase development work conducted on both sides of the Atlantic Ocean. We are honored to welcome Prof. Dr. Neidhöfer back to these pages as our guest history author for this issue of *IEEE Power & Energy Magazine*.

—Carl Sulzberger
Associate Editor, History

number of cycles (or the frequency)
= number of pole pairs times the speed of rotation

In this equation, the mechanical speed and the electric frequency are related to the same interval of time.

It was in the early 1890s that Westinghouse, with its star consultant Nikola Tesla, judged that lower operating frequencies would be better for the upcoming ac applications, mainly synchronous generators driven by low-speed engines, and rotating converters that would offer dc power for the many end-users.

83–133 Hz in Great Britain

Gisbert Kapp, a civil engineer from Westminster, London, with Austrian/Scottish roots, was well acquainted with the situation in England, on which he commented in 1894 in a German-language paper as follows (English translation):

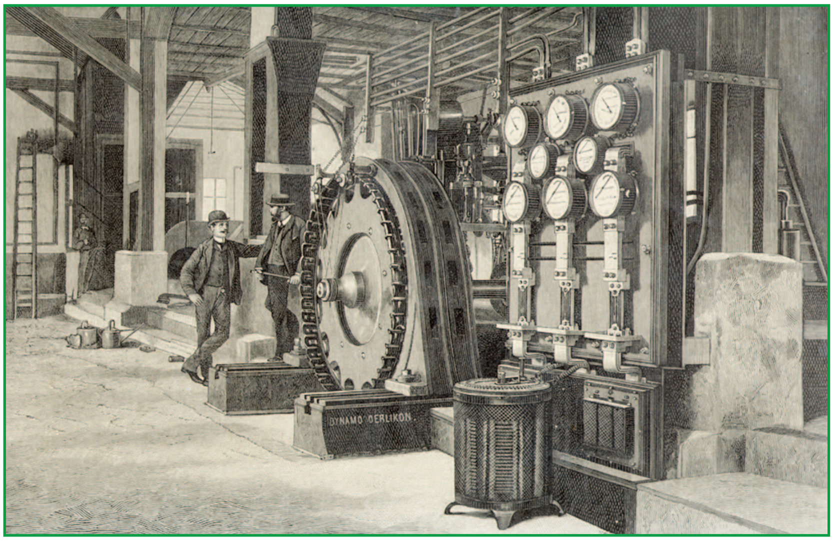

figure 1. Hydroelectric power station at Lauffen on the Neckar River, 1891, showing one of the 300-hp, three-phase ac generators having 32 poles and operating at 150 rev/min and 40 Hz (from a contemporary wood engraving).

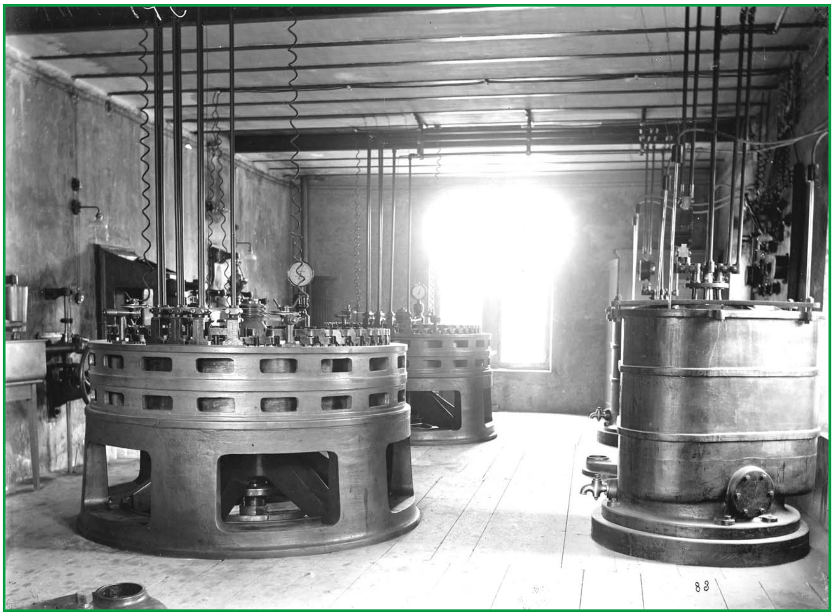

figure 2. Hochfelden hydroelectric power station near Zurich, 1892, showing "Type Lauffen vertical" three-phase ac generators operating at 187.5 rev/min and 50 Hz (photo courtesy of ABB Switzerland).

> …Up to now, the alternators were mostly belt-driven. But lately there has been a tendency towards direct coupling. So far, the main obstacle here was the high cycle numbers, ranging between 83 and 133 complete periods per second (10,000–16,000 alternations per minute). But for recent power stations one is going down with the cycle numbers. For instance, [the power station] Derby has only 40 cycles.… By this means, one is able to use relatively low-speed steam engines and directly coupled alternators with fewer poles.…

A statistical survey from the year 1900 on ac power stations in England confirmed 1) the preference of high frequencies under which 100 Hz clearly predominated but also 2) the trend toward lower values with a culmination at 50 Hz.

30–70 Hz in Continental Europe

On the European continent, rather moderate frequency numbers were preferred from the very beginning of the development of ac technology.

The Allgemeine Elektricitäts-Gesellschaft (AEG) in Germany and the Oerlikon Machine Company (MFO) in Switzerland cooperated in the field of ac power generation and transmission and initially agreed upon "a number of cycles of about 40 in general." In 1891, the companies installed and demonstrated the legendary three-phase power transmission from Lauffen on the Neckar River (see Figure 1) over 175 km (about 110 mi) to the International Electrical Exposition in Frankfurt on the Main River, and this with 40 Hz. In a closing lecture, the chief electrical engineer and ac-expert of AEG—Michael von Dolivo-Dobrowolsky, a nobleman of Russian origin—observed:

> As to the most favorable number of ac cycles, no sharp limits may be given. With three-phase induction motors, I prefer to apply rather low values, of about 30 to 40 cycles per second.

But he added, "in special cases one may apply higher values." Indeed, the partner company MFO had just decided on a 50-Hz power supply for its own factory, to be transmitted from a new hydropower station over a distance of 23 km (14.3 mi). See (Figure 2).

The generator for this power station, Hochfelden, was of the same type as in Lauffen but with a vertical axis and a new speed, raised from 150 to 187.5 rev/min. Accordingly, the frequency increased from 40 to 50 Hz (and the voltage increased in the same proportion). This adaptation is typical for the state of the art of those days: A given machine already constructed would be operated at new conditions of voltage and power, whereby the frequency was changed in the same proportion. In other words: an old machine model could be used without any structural change, but it would introduce another frequency.

Oerlikon in Switzerland deserves a special mention with regard to the early choice of 50 Hz. In his textbook from 1895, Prof. Silvanus Thompson wrote:

> From the autumn of 1891 the Oerlikon Machine Company has continued to develop the rotary field motor [three-phase ac induction motor], and has made many hundreds of different sizes.... The firm has adopted a standard frequency of 50 periods per second in its machines.... The Oerlikon Company has also constructed large alternators ...for the power stations at Bellegarde, Bremgarten and at Hochfelden... designed by Mr. C. E. L. Brown in 1890.

As the Hochfelden generators and those for Bremgarten were operated at 50 Hz, it is evident that the Oerlikon Machine Company (Zurich) had introduced 50 Hz already in 1890.

In Hungary, the Ganz Company decided upon 5,000 alternations as the company standard for more comfort with incandescent lighting. As outlined in the example above, 5,000 alternations equals 41 2/3 cycles/s, or slightly less than 42 Hz. With lower numbers, an arc-lamp light would be perceived as flickering and tiring for the human eye. As a consequence, in the marketing areas of the Ganz Company, Italy included, the frequency of about 42 Hz was widespread and used for decades.

A Mirror of Early Frequencies

In January 1918 during the AIEE Section Meeting in Washington, D.C., Benjamin Garver Lamme, the outstanding chief engineer of Westinghouse, presented his paper “The Technical Story of the Frequencies.” In a contribution to the discussion, H.B. Brooks commented, among other matters, on the scene abroad as follows:

> ...It may be of interest to glance at the frequency situation abroad. In Italy, which is poor in coal but rich in water power, five frequencies are in use, of which 42 cycles is in the lead, with 50 cycles a close second. Around Rome, 46 cycles is used, and there are also some 16 and 25-cycle installations throughout the country.

In 1934, in a survey, the long-serving chief engineer of Brown Boveri & Cie. (BBC) in Switzerland, Emil Hunziker, had a look back into the frequencies of his early generators (see Figures 3 and 4) and sketched a confusing situation. Translated from the German:

> ...Thus, among the power-station generators delivered by Brown Boveri we find frequencies from 37 to 55 cycles with

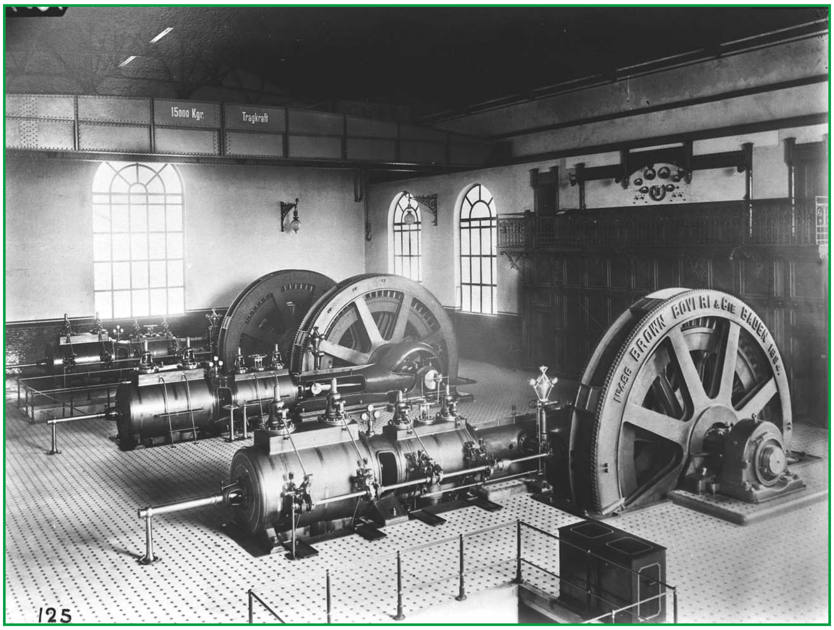

figure 3. Municipal power station at Frankfurt am Main, 1893, showing 750-hp, single-phase ac dynamos having 64 poles and operating at 85 rev/min and 45 1/3 Hz (photo courtesy of ABB Switzerland).

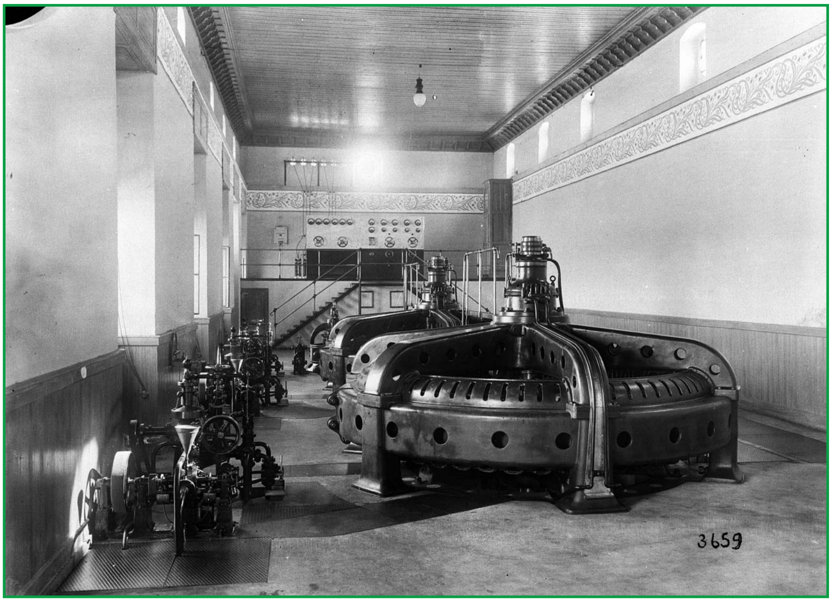

figure 4. Power station of the Festi-Rasini spinning and weaving mill in Milan, 1903, showing 810-hp hydroelectric generators having 60 poles and operating at 84 rev/min and 42 Hz (photo courtesy of ABB Switzerland).

many values in between, and a couple of deviations up and down.... I may mention some examples: Baden, Aarau, Olten-Aarburg 40, Cham 46, Interlaken 50, Frankfurt 45.3, Paderno 42, Killwangen 48, Arlen 38.6, Chèvres 46, Bellegarde 47.5, Bellinzona 65.3 cycles and so on. Larger Italian plants had chosen—following the standard of Ganz Co.—41.7 cycles corresponding to 5,000 alternations, a frequency which today is still quite widely spread besides the usual frequency 50....

Of course, other manufacturing companies with their specific markets may have had similar collections of installed frequencies.

The Search for the "Best" Frequencies

Basic Considerations

The jumble of alternation or cycle numbers challenged the experts of the time to look for favorable segments of frequency and, possibly, to specify preferential values. The main obstacle was the contradiction of two tendencies:

1) for electric lighting rather high frequencies were advantageous, with all the step-down transformers becoming much lighter and less expensive
2) for power systems, however, with generators, transmission lines, rotating converters and motors, lower frequencies would be more favorable.

Thus, the recommendation of a frequency was strongly dependent on the electric purpose of the system, and so on the population density and economy of a region, country, or even continent.

Good Advice

The Bohemian electrical expert Emil Kolben, who had been working with the Edison General Electric Company in the United States for five years and with MFO in Switzerland from 1892, knew very well the situation on both sides of the Atlantic Ocean. In 1893–1894, he stated that:

> Except for cases in which very high power is to be transmitted over particularly long distances, frequencies in the range of 50 to 60 cycles would best satisfy even high demands on economy, efficiency, control and operational safety.

Kolben's statement discloses a certain way of thinking to cut the Gordian knot, not to focus on one singular frequency for all purposes, but, if necessary, to select two typical frequencies, each of them being the best in their specific field.

The Solution in North America

Since the United States was the cradle of ac technology, the American frequency approach may first be indicated here in brief. As mentioned earlier, the tendency in the early 1890s was to drop the extra-high alternation numbers (133 or 125 Hz) and to adopt 60 Hz as a compromise for both electric system operation and engine-type generators, including rotating converters. Nevertheless, the European 50-Hz frequency was used in California in 1893–1894 when General Electric, obviously influenced by AEG from Germany, installed the Mill Creek generating project using 50 Hz, which shortly afterwards was changed to 60 Hz, as already used in that state (other 50-Hz areas continued to operate in Southern California until 1948).

Then, in 1895, a new aspect entered the scene with the completion of the first hydropower station at Niagara Falls. The giant ac generators, rated at 5,000 hp each (see Figure 5), had been designed to operate at a frequency of 25 Hz, a decision which had resulted from the various conditions involved, from the predetermined turbine speed via generator main design up to system operation. The fascinating debate concerning the most appropriate frequency (even 16 2/3 Hz was an option) can be followed in numerous articles. Niagara Falls became exemplary for North America in that most of the larger utilities and manufacturers were settling for two preferential frequencies: 25 Hz for transmission and synchronous converters and 60 Hz for more general-purpose systems. By about 1919, 25-Hz systems were slowly losing popularity in favor of the 60-Hz system as it was the fittest to survive for illumination and

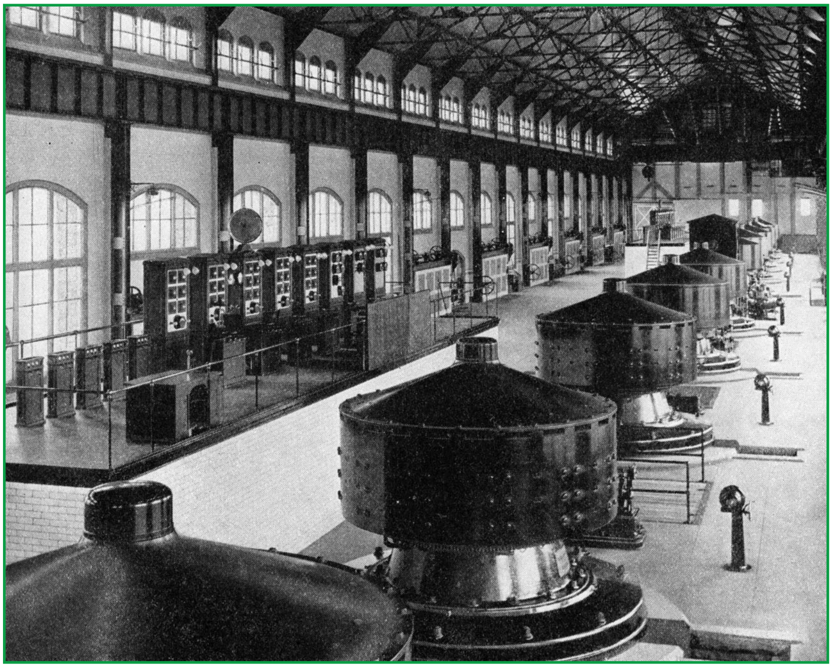

figure 5. Adams power station at Niagara Falls in the 1920s with the first three generating units installed in 1895 shown in the foreground. Each of these first 5,000-hp, two-phase hydroelectric generators had 12 poles and operated at 250 rev/min and 25 Hz (from E.D. Adams, *Niagara Power*, vol. 2, 1927, p. 73).

power distribution. Nevertheless, the use of 25 Hz was to last over decades and, in certain regions, even survive throughout the 20th century.

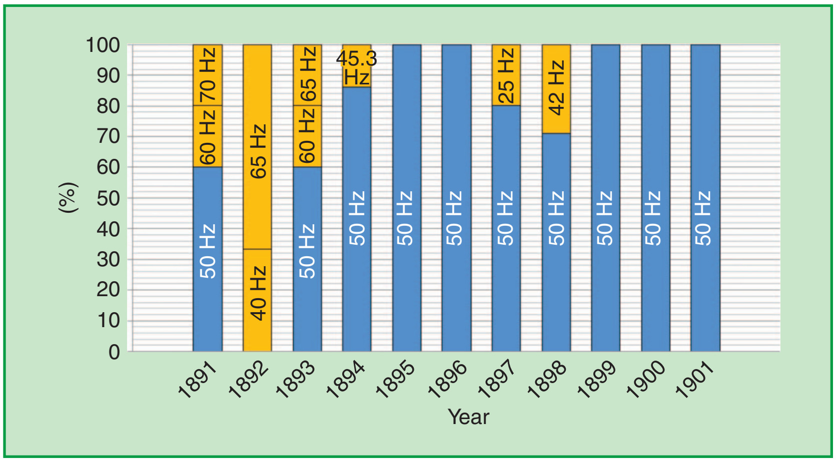

figure 6. Single-phase ac power stations erected in Germany between 1891 and 1901 with operating frequencies shown in percentages (data courtesy of VDE, the Association of German Electrical Engineers).

The Move Toward 50 Hz

1890–1900: Take-Off and Breakthrough

For 50 Hz, the 1890s was the decade of sporadic beginnings, growing preference and convincing breakthrough. Already in 1896, a treatise published by AEG on the Rheinfelden project noted

> the simple and prompt acquisition of motors, arc lamps and partially also transformers, since these products are manufactured by most European establishments precisely for 100 alternations (50 cycles).

A more detailed picture can be deduced from statistical material on "Single-Phase ac Power Stations Erected in Germany from 1890 to 1907," as indicated in a history booklet from the VDE (Association of German Electrical Engineers). Transformed into a diagram (see Figure 6), the trend becomes evident: Toward the middle of the decade the 50-Hz frequency goes on to predominate, relegating other cycle values to side issues. Among them is a single case of 25 Hz used in 1897 for a power station, the other values ranging between 40 and 70 Hz. It should be noted that most of such single-phase utilities primarily supplied power for electric lighting, for which a frequency of 40–60 Hz was simply the rule. When three-phase ac motors were developed and began to be used, 50 Hz was then consolidated as the preferred frequency once and for all.

1896–1897: AEG and Siemens Deliver to Japan

In 1896, the Tokyo Electric Light Company installed six hydrogenerators supplied by AEG and then, in 1897, the Keage Power Station received four hydrogenerators from Siemens, all operating at three-phase ac and 50 Hz. With these imports from Germany, Japan also imported the European 50-Hz frequency into a country in that, as a result of earlier deliveries from the United States, the 60-Hz American frequency had already been established. As a consequence, Japan today is electrically subdivided into two parts: 50 Hz northeast of Mount Fuji and 60 Hz to the southwest.

1898: Hydropower Plant Rheinfelden

Rheinfelden is a location on both sides of the Rhine River separating Germany and Switzerland along this upper section of the river. Here, the first large-scale hydroelectric power plant in Europe was erected, ranking directly after the Niagara power station in terms of power rating and year of commissioning. Figure 7 shows the power house with 20 hydroelectric units in total. Half of the units were designed to produce dc and the other half ac power: dc for adjoining electro-chemical plants

figure 7. Rheinfelden hydroelectric power station on the upper Rhine River, 1898, showing 850-hp, three-phase ac generators having 88 poles and operating at 68.2 rev/min and 50 Hz (photo courtesy of Energiedienst Holding AG Laufenburg).

figure 8. European interconnected network as shown in the 2008 annual report of the Union for the Coordination of Transmission of Electricity (UCTE).

and three-phase ac for lighting and power purposes for industrial plants and towns in both countries within a radius of about 20 km (12 mi). In view of such particular conditions, the planning engineers had to determine with care the most appropriate alternation number for this specific application.

Emil Rathenau, general manager of AEG in Berlin, stated in a survey dated 1896 (translated from the German):

> …After thorough investigations we decided for 50 periods per second, because with this alternation number the voltage-drop [in the transmission lines], caused by self-induction, can be held within reasonable limits; for the operation of transformers, motors and electric light bulbs this alternation number appears to be the best suitable, and also the use of arc lamps is permissible, as long as the demands on light-flicker are not excessive.…

AEG continued, in a resolute strategy, to establish municipal power stations at various places, thus paving the way for the widespread use of 50-Hz frequency. The Rheinfelden plant maintained a key position by expanding its service area, initiating cooperation arrangements with adjoining utilities, and gradually becoming the nucleus of the European interconnected network (see Figure 8).

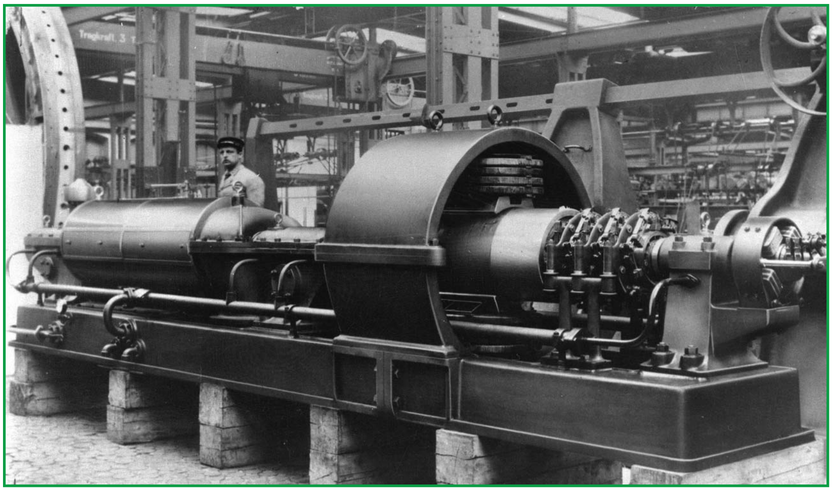

figure 9. Steam-turbine group for Wild & Abegg, Company, Turin, 1901, showing a 340-hp synchronous generator (external pole type) having two poles and operating at 3,000 rev/min and 50 Hz (photo courtesy of ABB Switzerland).

1901: First BBC Turbogenerator

The young BBC in Switzerland prepared to increasingly apply 50 Hz. The first steam turbine, built in 1901 on the European continent according to the English patent of the Parsons Company, operated at 3,000 rev/min. The direct-coupled turbogenerator had two poles and so produced ac power at 50 Hz (see Figure 9).

Around 1900: Real 50-Hz Standard

The list of new European plants operating at 50 Hz could easily be continued. There was a growing move in favor of this frequency that included more and more countries. Thus, 50 Hz ceased to be the exclusive province of German and Swiss manufacturers. By the turn of the 20th century, 50 Hz had become something of a customary standard; other preferential values such as 42 Hz were surpassed forever. All of these developments have led to the sometimes-heard opinion of today that 50-Hz frequency became a true standard by around 1900.

Why 50 Hz and Not 60 Hz?

For a final selection of the frequency, there was, at the beginning of the 20th century, a fairly narrow field of values to consider. The frequency had to be:

- ✔ rather low for power application: at about 25 Hz
- ✔ medium high for lighting purposes: at least 42 Hz
- ✔ rather high for the benefit of transformers: at least 60 Hz.

To meet these varying conditions with one single frequency, only a compromise could solve the problem. Viewed from the undoubted minimum of 42 Hz, the next higher ten-number was 50 Hz (exactly 100 alternations/s). The next ten-number, 60 Hz, was far-off and less advisable because the American 60-Hz frequency at that time seemed suitable only with a secondary 25-Hz frequency for large power requirements.

There is speculation that the value of 50 Hz was chosen in Europe as being an element in the metric "Series of Preferred Numbers," proposed by the French army engineer Charles Renard in the 1870s. Indeed, the R10 series, consisting of the following rounded values

10 12.5 16 20 25 31.5
40 50 63 80 100

expressly includes the number 50 but not the number 60. Whether such a consideration (preferred or arbitrary number) actually played a part in the final choice of a standard frequency cannot be confirmed.

The Fate of Non-50-Hz Utilities

Power stations that were run with another frequency had a difficult future and, at the latest on the occasion of extensions or renewals, had to convert to 50 Hz or close down. Three such cases are mentioned briefly.

The town of Heilbronn in southwestern Germany had been supplied from the hydropower plant Lauffen (see Figure 1) since 1892 and was privileged to be served by three-phase ac power. However, the frequency of 40 Hz caused the Heilbronn power system to become more and more set apart from more modern developments. The municipal power plant was forced to remain in isolated operation. It survived until 1925 but was prohibited from expanding into the adjacent electricity market served by 50 Hz power.

The first municipal power station at Frankfurt (see Figure 3) produced single-phase ac power at 45 1/3 Hz, beginning in 1893. The urbane Frankfurt society was well provided with electricity since the unusual value of the frequency was of no consequence for the primarily lighting installations. Later, when outside supplies from partner utilities operating at 50 Hz were needed, the incompatibility in frequency (and number of phases) caused much complication and required the installation of converters.

The town of Geneva, Switzerland, was supplied with electricity from an imposing hydroelectric power plant at Chèvres on the Rhone River, about 6 km (3.7 mi) downstream from Lake Geneva, near the border with France. Figure 10 shows the inside of the powerhouse after completion in about 1900. Fifteen large hydroelectric generators produced two-phase ac electric power at 46 Hz. These two singularities forced the power station to operate as an isolated electric island until 1943, when the plant was retired from operation and demolished.

50 Hz on the Way to Becoming a Standard

The settlement on a 50-Hz standard was very rapid in practice, but the promulgation and acceptance of this as a national

figure 10. Chèvres hydroelectric power station on the Rhone River, around 1900, showing two-phase ac generators having 46 poles and operating at 120 rev/min and 46 Hz, a first delivery lot had another combination of pole numbers and revolutions (photo courtesy of ABB Switzerland).

standard was slow and deliberate. The multistep process that occurred in Germany as well as the process that took place in several other European countries is considered in more detail.

Germany

VDE launched the first German standard for electrical machines and transformers in 1902, which occupied about three columns in the *ETZ (Elektrotechnische Zeitschrift)* of August 1903. The quantity called "frequency" was apparently a delicate one, having been placed in the annex only, with the wording (in an approximate translation from German):

> For new installations and in price lists it is advisable to consider, if possible, the following values for frequency, revolutions and voltage. The frequency should be 25 or 50.

The text continued with a specification of preferred revolutions and voltages. The tricky situation with the frequency was a real dilemma, as commented in more detail by Georg Dettmar, the chairman of the committee:

> It seemed desirable to establish standards for frequency, voltage, and revolutions etc., being quite aware that these points could not be an object of regulations because this would interfere too much in both the production of the various companies and the economic efficiency of the systems. Nevertheless, for giving a guide and to form a base for possible regulations later on in this direction, it was agreed to edit these particular items not as regulations but only to recommend them in the annex. As a consequence, the standard items of the annex are not binding, the Association of German Electrical Engineers only recommends to follow these standards as far as possible.
>
> On the whole in Germany, one has succeeded to apply the frequency of 50 (= 100 alternations per second, in the former term) quite generally, so that in this respect, regulation could be fairly easy. There are only a few systems installed with other frequencies, of which 42, 40 and 25 should be mentioned. The latter is a possibility for real power application and has decisive major advantages compared with the frequency of 50. Consequently, one has decided to include the frequency 25 as a standard, too. Thanks to these two values, one is in a position to realize every installation in an efficient manner.

Also in 1903, Oskar von Miller, a prominent expert for the supply of [German] towns with electricity, confirmed

> that with respect to the use of motors on the one hand and the application of electric lighting on the other, 50 periods per second is not only desirable but almost universally accepted.

Ten years later, in 1912, the German standards committee stated that the frequency of 25 Hz had not found regular use in power applications. So the revised version, effective beginning

1914, recommended a single value of frequency only, this being 50 Hz.

It took many more years before the frequency was upgraded to a true standard quantity in a revised version, effective beginning 1930. Thus, the lengthy process, initiated in 1902, finally ended with the very modest and simple clause:

"The standard frequency is 50 Hz."

Austria

In Austria, there were continuous efforts to ensure, if at all possible, parallelism with the German rules for electrical machines and transformers. In 1917, the national committee launched the first standards in which 50 Hz was recommended. Already in 1920, the standards became effective. Toward the end of the 1920s, the compatibility of the two systems was demonstrated when a legendary high-voltage transmission line came to interconnect the alpine hydroelectric power in Vorarlberg (western Austria) with the West German brown-coal district over a distance of about 800 km (500 mi).

Switzerland

Switzerland is the one country with probably the first choice and preferred application of 50 Hz. So the country supported 50 Hz from the very beginning with power stations such as Hochfelden (1892), Bremgarten (1895), Rheinfelden (1898), Beznau (1903), and others. Beginning in 1918, actions were undertaken to harmonize and strengthen the Swiss electrical network by a confederate busbar, on the basis of high-voltage, three-phase ac and 50 Hz extending from Lake Constance across the Swiss midland to Lake Geneva over a distance of about 300 km (190 mi).

For the Swiss electrical scene, the German standard situation was initially the determinant. Beginning in 1934, national rules were promulgated, which were basically derived from the International Electrotechnical Commission (IEC) publication, which recognized frequencies of both 50 and 60 Hz. Within the territory of Switzerland, 50 Hz was an early standard by fact and consensus.

Great Britain

In Great Britain there was a particularly large variety of system frequencies, ranging between 40 and 100 Hz with 11 intermediate values, as shown in the 1900 statistical survey mentioned earlier. The special situation in London found attention at the 1918 AIEE Section Meeting held in Washington, D.C., in an extra comment, as follows:

> …London is probably the worst example of the independent growth of small detached generating systems with no thought of possible future interconnection. Merz and McLellan studied the situation and made a report in 1914 to the London County Council, from which it appeared

that there were in the central area of London 41 generating stations representing 31 systems and 8 frequencies. The report advocates the adoption of 50 cycles as a standard frequency for London.

The introduction of a national standard frequency in Great Britain occurred much later when the Central Electricity Authority, formed in 1925, began to create a high-voltage interconnecting network operating at 50 Hz. The standard was completely established in Great Britain only after World War II.

In Retrospect and More Recent Matters

The Frequency Story, Marked by Monopoly and Pragmatism

Readers who expected to learn a straightforward history of the 50-Hz standard may feel only partially satisfied. In fact, both the initiation and propagation of the 50-Hz frequency was a puzzling process in itself, with various levels of confusion in the countries concerned. Even more complex and protracted was the route to national standards, which often came to a close under the monopoly of a few manufacturing companies and the pressures of technical reality.

Repeatedly quoted is H.B. Brooks. In January 1918, he identified the main reason for the frequency confusion simply as being the large number of manufacturing companies and gave examples to show the opposite situation:

> . . . In contrast to the medley of plants and frequencies in London, the cities of Hamburg and Berlin each have electric [power] supply from a single company. The frequency of the Berlin system is 50 cycles. The business in Paris is [also] practically all in the hands of a single company, operating at 25 and 42 cycles. . . .

The overall consequence is simply this: the fewer manufacturing companies involved, the better for conforming frequencies. Thus, the somewhat pejorative notion of "monopoly," as occasionally associated with AEG in Germany and 50 Hz, may appear in a more favorable light. In actual fact, the said firm was not all alone with regard to early 50 Hz since the partner company MFO in Switzerland had adopted 50 Hz as a product standard even before AEG.

Interconnected 50-Hz Network of Continental Europe

Having a common frequency in European countries was the absolute precondition for the interconnection of the electrical systems concerned. What at first was the simple connection of a few power plants in parallel for mutual assistance progressively became an extended meshed network having the purpose of reliability and cost savings for all system players. Soon after World War II, transborder power exchange between continental European countries was initiated. A pioneering venture was a high-voltage interconnection involving France, Germany, and Switzerland in 1958. This "Star of Laufenburg" interconnection was named an IEEE Milestone in 2010. Meanwhile, the UCTE (Union for the Coordination of Transmission of Electricity) includes 23 continental European countries that are interconnected in a huge grid extending across the continent from Portugal to Denmark, Poland, Greece, and Spain and that also includes the Mediterranean islands (see Figure 8). This power network is synchronously interconnected and necessarily operates with the beat of one single frequency, which of course is 50 Hz.

Hydropower Plant Itaipu: A Recent 50 Hz / 60 Hz Conflict and Its Solution

The electrical world has learned to manage with the two different frequency standards (50 Hz and 60 Hz), in most cases by installing independent and, unfortunately, incompatible systems. But in certain situations, the two normally quite coexisting standard frequencies risk conflict within one and the same complex.

A particular such configuration arose toward the end of the 1960s, when the gigantic Itaipu hydroelectric power project in South America was in the planning stage. Itaipu is a binational power plant operated by Brazil and Paraguay at the Paraná River on the common border section between the two countries.

The conflict was that the two countries are owners in equal shares, but the standard frequencies differ (Brazil is at 60 Hz, and Paraguay is at 50 Hz) and the greater portion of the produced energy was to be consumed in Brazil.

After some alternative solutions had been considered and abandoned, a combined political/technical breakthrough was found: Half of the generating units would operate at 50 Hz (90.9 rev/min, 66 poles), the other half at 60 Hz (92.3 rev/min, 78 poles), the two generator variants being driven by the same model water turbine. Most of the "Paraguayan" energy produced at 50 Hz, for the time not needed in Paraguay, would be converted into dc power by static rectifiers in the plant and transmitted along two high-voltage dc lines, over a distance of about 800 km (500 mi) to São Paulo, Brazil, where terminal equipment would convert the power to 60 Hz ac power. The "Brazilian" energy from Itaipu produced at 60 Hz would be transmitted directly as high-voltage three-phase ac.

In 1984 the first generating unit began operating (see Figure 11), and in 1991 the power plant was completed with a total of 18 units, each producing about 700 MW. Two additional units were installed in 2006–2007.

In conclusion: The Itaipu electric system conflict, caused by the incompatibility of the two major frequency standards of our globe, is a fascinating example of a possible collision between systems and also a showcase for the skillful resolution of an electric conflict by applying thoughtful electrical solutions.

figure 11. One of the first hydroelectric generators installed in the Itaipu hydropower plant, 1984. Half of the generating units operate at 50 Hz, and the other half operate at 60 Hz (photo courtesy of ABB Switzerland).

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