The Earliest Years of Three-Phase Power—1891–1893

By Adam Allerhand

This article is about the earliest innovations in polyphase power, with an emphasis on three phases. Inventions are presented when necessary to describe products, which is why the inventions of Michael von Dolivo-Dobrowolsky, Friedrich August Haselwander, Nikola Tesla, and Jonas Wenström make an appearance while those of Galileo Ferraris and Charles S. Bradley do not.

The month's history article provides a comprehensive analysis of an important development in electric power, namely the acceptance of three-phase AC transmission of electricity.

Long-distance high-voltage single-phase ac transmission was ubiquitous by 1890, notably the systems built by Westinghouse Electric Co. of the United States and Ganz & Co. of Hungary [1]. The catalyst for the deemphasis on single-phase ac power and the commercial implementation of long-distance polyphase transmission in the 1892–1893 period was the 175-mi three-phase power line from Lauffen to Frankfurt during the 1891 Frankfurt Electrical Exposition, designed and built by the German firm Allgemeine Elektrizitäts Gesellschaft (AEG) and the Swiss firm Maschinenfabrik Oerlikon. Carl Hering, the Chairman of the delegation from the American Institute of Electrical Engineers to the International Congress of Electricians [2] held in conjunction with the exposition, commented about the impact of the Lauffen–Frankfurt experiment [3]:

> The occasion of the transmission of power from Lauffen to Frankfort has brought to the notice of the profession more than ever before the two or three phase alternating current system, described as early as 1887-8 by various electricians, among whom are Tesla, Bradley, Haselwander and others. As to who first invented it, we have nothing to say here, but though known for some years it has not until quite recently been of any great importance in practice.

The lack of excitement about polyphase power transmission before the 1891 Frankfurt Exposition is apparent in Tesla's description of "a novel system of electric distribution, and transmission of power by means of alternate current" at a meeting of the American Institute of Electrical Engineers on May 16, 1888 [4]. The lecture was almost entirely about motors. He did not mention the advantages of his invention for the general-purpose transmission of power[1] even though he did so in a patent filed in 1887 [5].[2] The Westinghouse Electric Co., the owner of Tesla's polyphase patents, announced Tesla generators and motors in 1888 [6], but Westinghouse's first foray into polyphase power transmission was a two-phase demonstration system five years later [7]. Financial difficulties contributed to the delay (see Section III).

The Lauffen–Frankfurt transmission was not the only revelation of polyphase power at the exposition. AEG and Oerlikon exhibited three-phase equipment, as did the German firms Lahmeyer & Co. and Siemens & Halske. The exposition also featured two-phase machinery plus a 4-km two-phase transmission line by the German firm Schuckert & Co. and a 10-km three-phase transmission line by Lahmeyer [8].

The Lauffen–Frankfurt transmission system, designed and engineered by Michael von Dolivo-Dobrowolsky of AEG in collaboration with Charles Eugene Lancelot Brown of Oerlikon (see Fig. 1), became operational near the end of August 1891 [9], but its story starts in March 1891 when

[1]Tesla biographers Thomas Commerford Martin (1894), J. J. O'Neill (1944), Mark J. Seifer (1998), and W. Bernard Carlson (2013) do not comment about the fact that Tesla did not present his invention as a general purpose tool for long-distance transmission of electric power.

[2]My present invention is a new method or mode of effecting the transmission of power by electrical agency, whereby many of the present objections are overcome and great economy and efficiency secured.

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Fig. 1. *(Left) Michael von Dolivo-Dobrowolsky. (Right) Charles E. L. Brown. Public domain images from Wikimedia Commons.*

Dolivo-Dobrowolsky described his three-phase system in a German article titled "Kraftübertragung mittels Wechselströmen von verschiedener Phase (Drehstrom)" [10] and in an English version in April–May of that year [11]. The word Drehstrom, an abridgement of Dreiphasenwechselstrom (three-phase ac), was coined by Dolivo-Dobrowolsky in his German article, and he translated that German word into "three-phase current" in his English article [11].

Expecting controversy about the priority of invention, Dolivo-Dobrowolsky fired a preemptive salvo within his article. Excerpt from the English version:

> . . . Tesla's arrangement, with two entirely independent currents differing by 90 deg. in their phases, was not particularly advantageous; its faults were avoided in other arrangements, and motors with a greater number of alternate currents were contemporaneously studied by Bradley, and the present writer, Haselwander, and Wenström. At the same time (October, 1888) as Bradley applied for the American patent for his three-wire connection from a Gramme armature, the present writer also was working in the Allgemeine Elektricitäts Gesellschaft on a three-phase motor, and Haselwander was also experimenting at Offenburg. In March, 1889, the Allgemeine Company applied for a patent on this subject; in consequence of some formality or error, the patent was only partially granted. As the preliminary measures for constructing such motors and some improvements in detail claimed the whole time of this firm, the second amended application was kept back till August. During this pause – namely, in June – Haselwander made an application for a patent bearing on the same subject. . . . Altogether it is extremely difficult, out of the crowd of suddenly published researches and applications for patents, to definitely adjudge the priority of the idea to the one or the other of the inventors named . . . But the technical priority incontestably belongs to the person and the firm who gave vitality to the invention, and who first produced a useful technical piece of apparatus . . .

In some of his patents, Dolivo-Dobrowolsky acknowledged the earlier inventions of Bradley, Ferraris, and Tesla, asserting that his inventions were improvements. Tesla published a rebuttal in 1892 [12]. Excerpt:

> . . . had the patents been carefully studied by others there would not have been various features of my system reinvented . . . I do not think that in Germany, where the Patent Office is proverbially strict in upholding the rights of the inventor, an illegitimate and unfair appropriation of the invention by others will be tolerated by the courts.

Wenström has a peculiar place in the timeline of three-phase power. He was already testing three-phase prototypes based on his patent in 1890, and the company that was created to translate his invention into a commercial system, Allmänna Svenska Elektriska Aktiebolaget (ASEA), was formed in February 1891, before the Frankfurt Exposition began. However, the first ASEA three-phase transmission system became operational in December 1893 when there were already many commercial three-phase systems operating in Europe (see Table 1). Nevertheless, my story would be incomplete without a detailed description of early three-phase power in Sweden because almost nothing has been written about it in languages other than Swedish. Furthermore, ASEA had only 170 employees in 1893 but became an industrial giant. In 1987, ASEA merged with Brown, Boveri of Switzerland to form ABB, the largest manufacturer of heavy electrical equipment today, being fifth in the world market in 1999 [13]. Friedrich August Haselwander's three-phase system also predates the 1891 Frankfurt Exposition. Haselwander is honored in his hometown of Offenburg, Germany, as the first to construct a viable three-phase generator [14]. More about Haselwander is given in Section I.

Because I omit post-1893 systems, this will be largely a European story. The only American three-phase system described in detail will be the one installed in 1893 by the General Electric Company. The entry of General Electric into the three-phase business merits some comments. Thomas Edison's losing war against alternating current near the end of the 1880s caused the end of his career in the electrical business when financiers forced the merger of Edison's various electric companies into the misleadingly named Edison General Electric (EGE) Company in 1889. However, EGE was not in a good position to enter the ac power business, having inherited no ac expertise from Edison's companies. In the mid-1892s, EGE merged with the Thomson-Houston Electric Co., a major supplier of single-phase ac power for electric trains, to form General Electric, under the management of Thomson-Houston leaders [15]. Why the very young GE, with no polyphase experience, was willing and able to begin the construction of four commercial three-phase transmission systems in 1893, two

Table 1 Earliest Commercial Three-Phase AC Transmission Systems (1892–1893)

Start	kW	Hz	Generation Volts	Transmission Volts	km	Owner or other information	Manufacturer
1892	340	40	50	5,000	10	Lauffen-Heilbronn, Germany	Oerlikon and AEG
1892	220		80	660	1	Bockenheim (Frankfurt), Germany	Lahmeyer
1892	95			5,000	17	Spreitenbach-Wiedikon, Switzerland	Oerlikon
1892	335	50	50	13,000	19	Bülach-Oerlikon, Switzerland	Oerlikon
1893	200	40	80	1,800	3	Biel, Switzerland	Lahmeyer
1893	80	50	1,500	1,500	4	Erding, Germany	Siemens & Halske
1893	80		120	5,000	4	Elgóibar and Elbar, Spain	Siemens & Halske
1893	150			5,200	9	Wangen, Germany	Oerlikon
1893	75		1,000	1,000	2	Pergine, Austria-Hungary (now Italy)	Oerlikon
1893	750		230	230	1	Novorossiysk, Russia	Brown, Boveri
1893	500	50	2,500	2,500	12	Redlands Elec. Light & Pwr. Co., CA	General Electric
1893	300		700	7,000	18	Hartford, CT	General Electric
1893	300	70	150	5,000	14	Hellsjön-Grängesberg, Sweden	ASEA

of them becoming operational that year, will be discussed in Section II.

I end this section with comments about early high-voltage dc (HVDC) transmission because experience with HVDC was an important prelude to Oerlikon's and ASEA's entry into high-voltage three-phase ac transmission. Most narratives about the so-called "battle of the currents" of the 1887–1889 period list only short-distance low-voltage dc transmission and long-distance high-voltage single-phase ac transmission when, in fact, HVDC was a third commercial competitor in Europe. The story of HVDC begins at the Vienna Universal Exhibition of 1873, where Société des Machines Magnéto-Électriques Gramme exhibited a short-transmission system in which a low-voltage Gramme dc dynamo was connected to a similar dynamo running in reverse as a motor [16]. The feasibility of HVDC (for powering motors) became apparent at the Munich Electrical Exposition of 1882, where a French electrical engineer, Marcel Deprez, connected a 1500-V Gramme dc dynamo located 57 km from the exposition to another such dynamo running in reverse as a motor at the exposition [17]. The Oerlikon and ASEA commercial HVDC transmission lines also terminated at HVDC dynamos running in reverse.

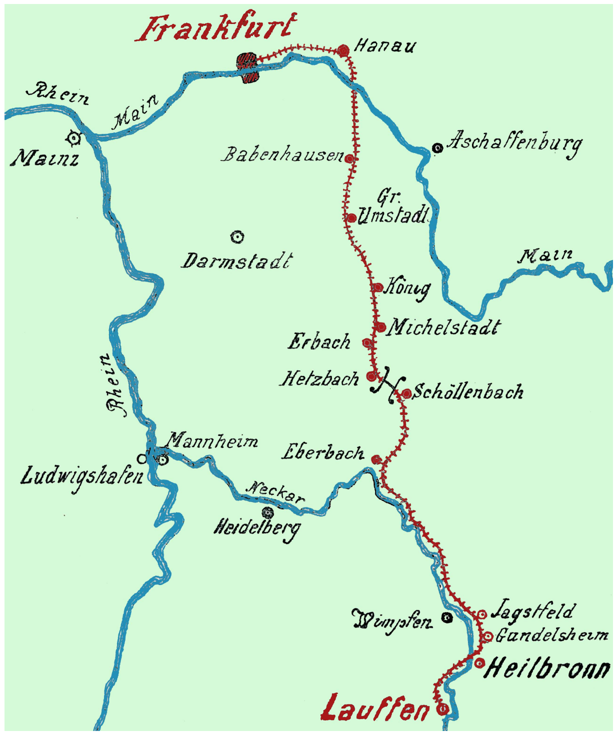

Fig. 2. *Map of the Lauffen–Frankfurt transmission line, adapted from [8].*

I. 1891—THE FRANKFURT ELECTRICAL EXPOSITION

As an organizer of the 1882 Munich Electrical Exposition, young engineer, Oskar von Miller, arranged for Marcel Deprez to implement his HVDC power line [17]. In 1883, German entrepreneur, Emil Rathenau, acquired the rights to Edison's patents for Germany and with funding from bankers founded Deutsche Edison-Gesellschaft für angewandte Elektrizität [18]. Oskar von Miller joined that company in 1884, which, in 1887, became AEG. He created his own engineering company in 1889 [19]. Von Miller was the technical director of the Frankfurt Electrical Exposition of 1891 and the driving force for making the 175-km 200-kW three-phase transmission at 14 000–29 500 V from Lauffen to Frankfurt a reality [8]. It required diplomatic talent to get a German manufacturer and a Swiss one to cooperate and know-how to overcome bureaucratic hindrance by the Reich government and officials of localities in the path of the transmission line (see Fig. 2) [20].

The Frankfurt Exposition was the brainchild of Leopold Sonnemann, an influential political leader and publisher of the Frankfurter Zeitung. The exposition was open from May 15 to October 15 in 1891 [8]. It published 30 issues of an illustrated weekly periodical, *Offizielle Zeitung*, for a total of 1028 pages [8], and a two-volume report, *Offizieller Bericht* [21], [22]. There were articles about

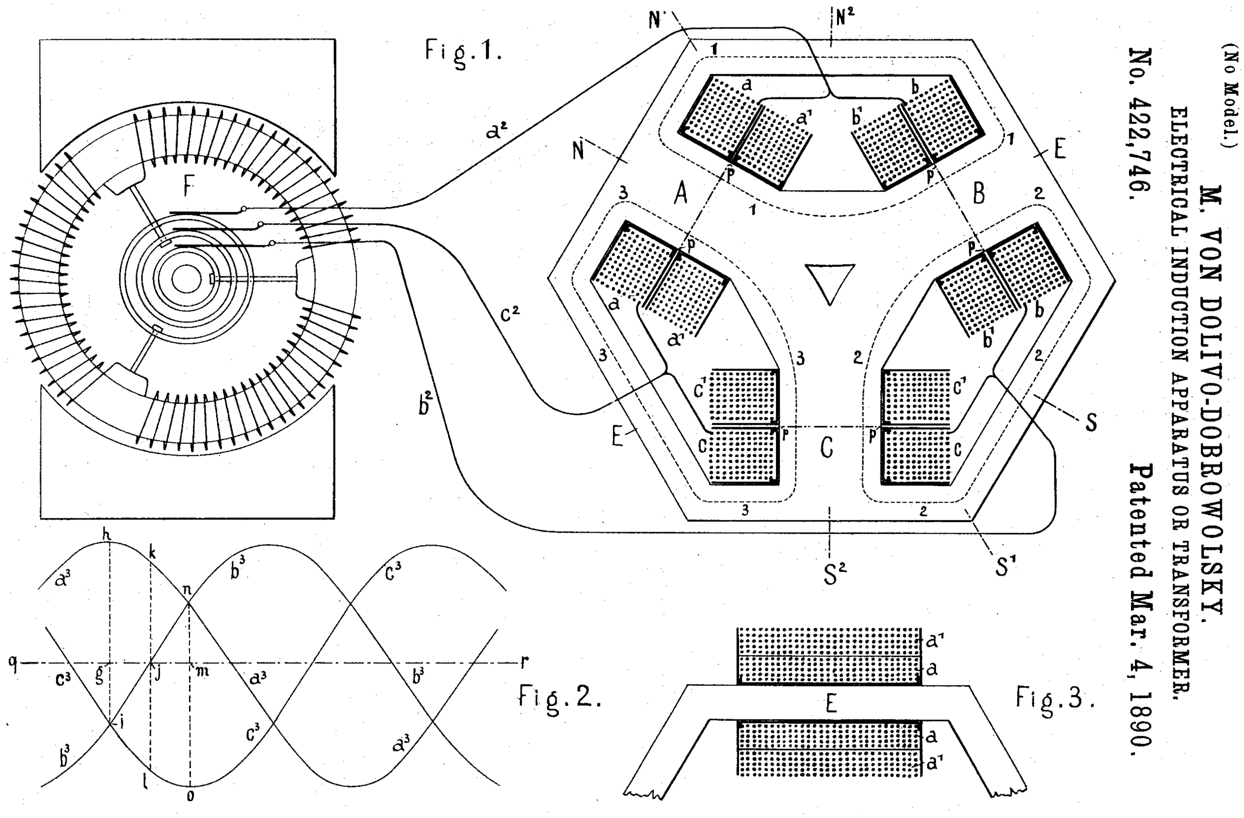

Fig. 3. ***Illustration from Michael von Dolivo-Dobrowolsky's United States patent for a three-phase transformer, No. 422,746, filed January 8, 1890, assigned to AEG.***

the exposition and the Lauffen–Frankfurt transmission in trade periodicals of many countries. A British reporter summarized the construction in an article published on May 29, 1891 [23]:

> This "Drehstrom System" is a multiphase transmission which will be adopted in the experiment between Lauffen and Frankfort, and which is carried out jointly by the Portland Cement Works at Lauffen, which puts its 300 H.P. turbine at disposal, the Maschinenfabrik Oerlikon, and the Allgemeine Electricitäts Gesellschaft, which supply the dynamo, transformers and instruments at the generating station, motors and insulators, and lastly the Government which undertakes the erection of the conductors—three wires of 4 mm. diameter, each of 175 kilometers in length. The intention is to work with a pressure of 25 000 volts. ...For this transmission 2600 telegraph posts, 9000 fluid insulators and about 60 tons of copper wire will be used. The details of the design are carried out by Mr. Brown, of Oerlikon, and Mr. Dobrowolsky, of Berlin.

Russian-born Michael von Dolivo-Dobrowolsky joined AEG in 1887 and was its Chief Engineer at the time of the exposition [24]. He had a working prototype of a three-phase motor in 1889. From 1889 to 1891, Dolivo-Dobrovolsky and AEG applied for three-phase patents in Britain, Germany, Switzerland, the United States, and other countries, most of them granted by the end of 1891[3] [25] (see Fig. 3). The Swiss corporation, Maschinenfabrik Oerlikon, was founded in 1876, headed by industrialist Peter Emil Huber-Werdmüller [26]. Manufacturing of electrical equipment began in 1884 under the direction of Charles E. L. Brown. Initially, Brown developed HVDC transmission systems [27]. In December 1886, an Oerlikon hydroelectric plant in Kriegstetten (Switzerland) began transmitting 2500-V 37-kW power to two motors at a clock-making factory in Solothurn, 8 km from the power plant [28]. By the end of 1889, there were 13 Oerlikon HDVC transmission systems in five European countries, eight of them powering motors in textile mills [29, Table II]. Brown leveraged his expertise with HVDC to the design of dynamos and power lines of the Lauffen–Frankfurt experiment.

Oskar von Miller's experience at the 1882 Munich Exposition involved 1500-V dc transmitted about 57 km [17]. He was not able to find any source of adequate hydropower 50–60 km from Frankfurt in 1891. He chose Lauffen by default because a cement factory there offered adequate hydropower. However, the 175-km distance to Frankfurt

[3]Most of Dolivo-Dobrowolsky's early Drehstrom patents are listed on pp. 254–255 of [24].

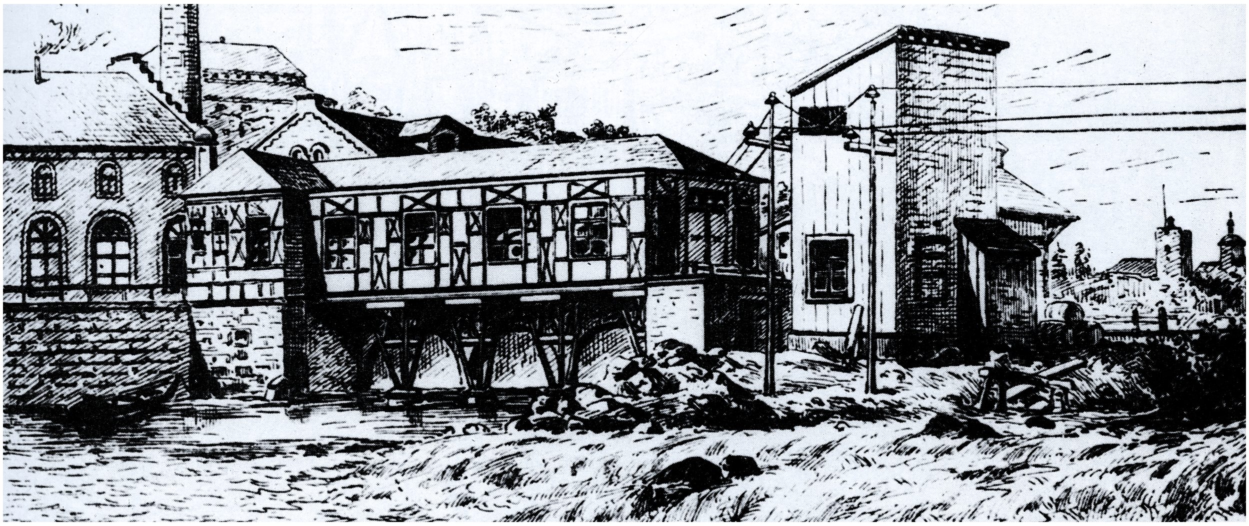

Fig. 4. *Exterior of the Lauffen power plant in 1891. Illustration from Kleine Presse (Frankfurt) of August 20, 1891.*

would require a much higher voltage than ever used before for electric power transmission. Miller was familiar with Brown's HVDC work, and during a visit to Oerlikon in 1890, he asked Brown if it would be possible to generate 25 000-V power. Brown thought it would be possible by using oil as an insulating material in transformers [19]. He was not the first to think of oil as a high-voltage insulator, but it was only after the success of the Lauffen–Frankfurt experiment that oil as a high-voltage insulator became a fashionable topic among electrical engineers and a source of discussion about who was "first" [30].

After preliminary negotiations, AEG and the Exposition Board signed a detailed agreement on December 6, 1890. Most importantly, it stipulated that Oerlikon set up a high-voltage pilot plant in order to enable German officials to judge the admissibility of high-voltage current. Brown put a pilot plant into operation in November 1889 [31]. Exposition officials and representatives of telegraph and railway authorities visited Oerlikon in January 1891 [8]. They watched as Brown stepped up 110-V dc to 33 000 V in his newly devised oil-filled transformer, passed it through a 7-km wire, and transformed it back to 110 V, which powered electric lights [32].

For the exposition, Oerlikon supplied the generator and two transformers; AEG supplied control panels, two transformers, and a motor. Brown, having successfully developed 1250-V dc generators, realized that he was not yet up to the task of constructing a viable high-power high-voltage three-phase generator. Instead, he constructed a 32-pole, 50-V generator running at 150 rev/min (40 Hz), capable of yielding a current of about 1400 A. Such a high current required innovative design features [33]. Figs. 4 and 5 show the power plant exterior [34] and interior [35], respectively. A transformer upconverted to voltages in the range 14 000–29 500 for power and efficiency tests. A transformer in Frankfurt downconverted to 65 V for powering incandescent lights and an artificial waterfall driven by an electric pump (see Fig. 6).

Brown and Walter Boveri, a Manager in Oerlikon's electrical division, left Oerlikon when the exposition was ending to form Brown, Boveri, & Compagnie (BBC) [36], which eventually became yet another Swiss industrial powerhouse [37]. Brown, Boveri's first polyphase transmission system, in 1892, was a two-phase system.[4]

The spectacular Lauffen–Frankfurt transmission overshadowed the three-phase exhibit of the German firm Siemens & Halske, the two-phase exhibit and 4-km 1600-V two-phase transmission line of the German firm Schuckert and Co., and the three-phase exhibit of the German firm Lahmeyer & Co., which included a 10-km 1300-V transmission line of three 6-mm-diameter wires from Offenbach (now part of the Frankfurt urban area) to the exhibition grounds, where the high ac voltage was converted to 110-V dc [21].

Lahmeyer exhibited a three-phase generator based on the design of Friedrich August Haselwander (see Fig. 7) [8]. Haselwander summarized his 1887–1888 three-phase work at a meeting of the German Electrotechnical Association just before the exposition began [39]:

> The machine was put into operation on October 12, 1887. . . . By July of 1887 I had already completed the basic idea of three-phase power transmission, consisting of two Thomson-Houston machines whose collectors were removed and whose armature coils were self-contained at one end and connected by wires at the other end. . . . My first patent application, dated July 21, 1888, contains everything essential to what is today called the three-phase system. . . . My patent is now owned by W. Lahmeyer & Co. of Frankfurt. . .

[4]Letter from Walter Boveri dated Apr. 21, 1891 to Louis Theodor Pfister with the delivery conditions for two two-phase generators of 200 hp, 1000 V, and 40 Hz, for the Kappelerhof district in Baden, Switzerland. Cited in [38].

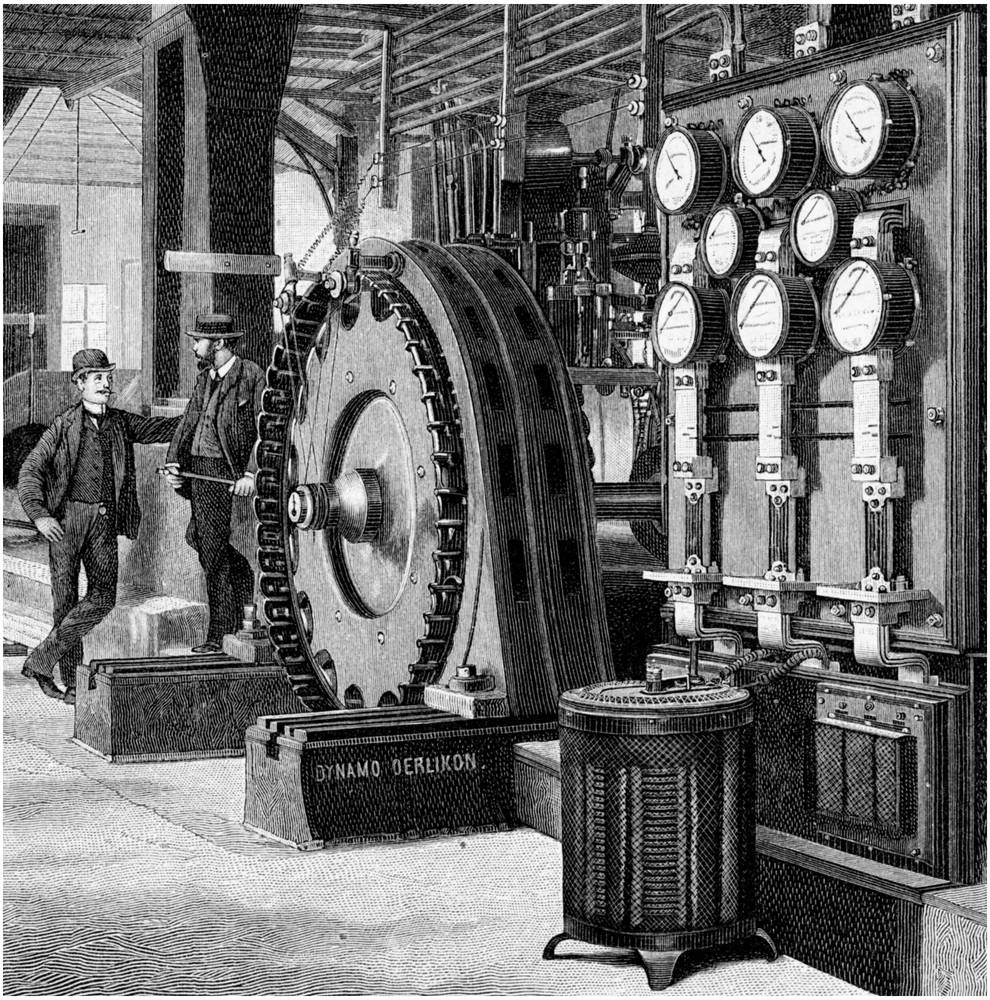

Fig. 5. *Interior of the Lauffen power plant in 1891. Illustration from [35].*

Indeed, Centralblatt für Elektrotechnik (Munich) of December 1887 reported on Haselwander's small generator, mainly numerical data (330 kg, 110-V, 18 A) [40]. Haselwander applied for a German patent for his three-phase generator on July 21, 1888; a slightly revised application was resubmitted on June 30, 1889. The patent (No. 55,978) was granted on February 2, 1891 [41], [42]. On January 6, 1892, the German Patent Office invalidated the novelty of the essential part of Haselwander's patent, based on Tesla's American patents [42].

II. 1892–1893—FIRST COMMERCIAL THREE-PHASE POWER TRANSMISSION SYSTEMS

Table 1 lists commercial three-phase transmission systems of the 1892–1893 period,[5] omitting a few that I found mentioned but not described. There were already commercial three-phase systems operating in Germany and Switzerland in 1892 but over much shorter distances than the 175 km of Lauffen–Frankfurt. In the United States, only General Electric embraced three-phase power promptly. The other makers of polyphase systems, Westinghouse Electric & Mfg. Co. and Stanley Electric Mfg. Co., placed their bets on two-phase power (next section). Britain and France are absent from Table 1. There were three three-phase systems under construction in France in 1893 [43]. The first three-phase installation in Britain occurred much later, in 1897 [44]. The reason for that delay is beyond the scope of this article.

A. 1893 Hellsjön–Grängesberg Transmission System in Sweden

Iron mining was the driving force for the development of high-power electric transmission in Sweden. The three-phase transmission system from the hydroelectric station at Hellsjön to the Grängesberg mines, about 8–14 km from Hellsjön, became operational in December 1893 [45], [46]. Starting in 1894, the machinery at the mines could be run by electric motors instead of mechanical methods, and the mines could function around the clock with electric lights installed. The mines' output increased only 6% from 1892 to 1893, but it increased by 50% from 1893 to 1894 [47]. The Hellsjön–Grängesberg

[5]I searched trade periodicals of the 1891–1896 period in Austria, Britain, Canada, France, Germany, Holland, Italy, Sweden, Switzerland, and the United States.

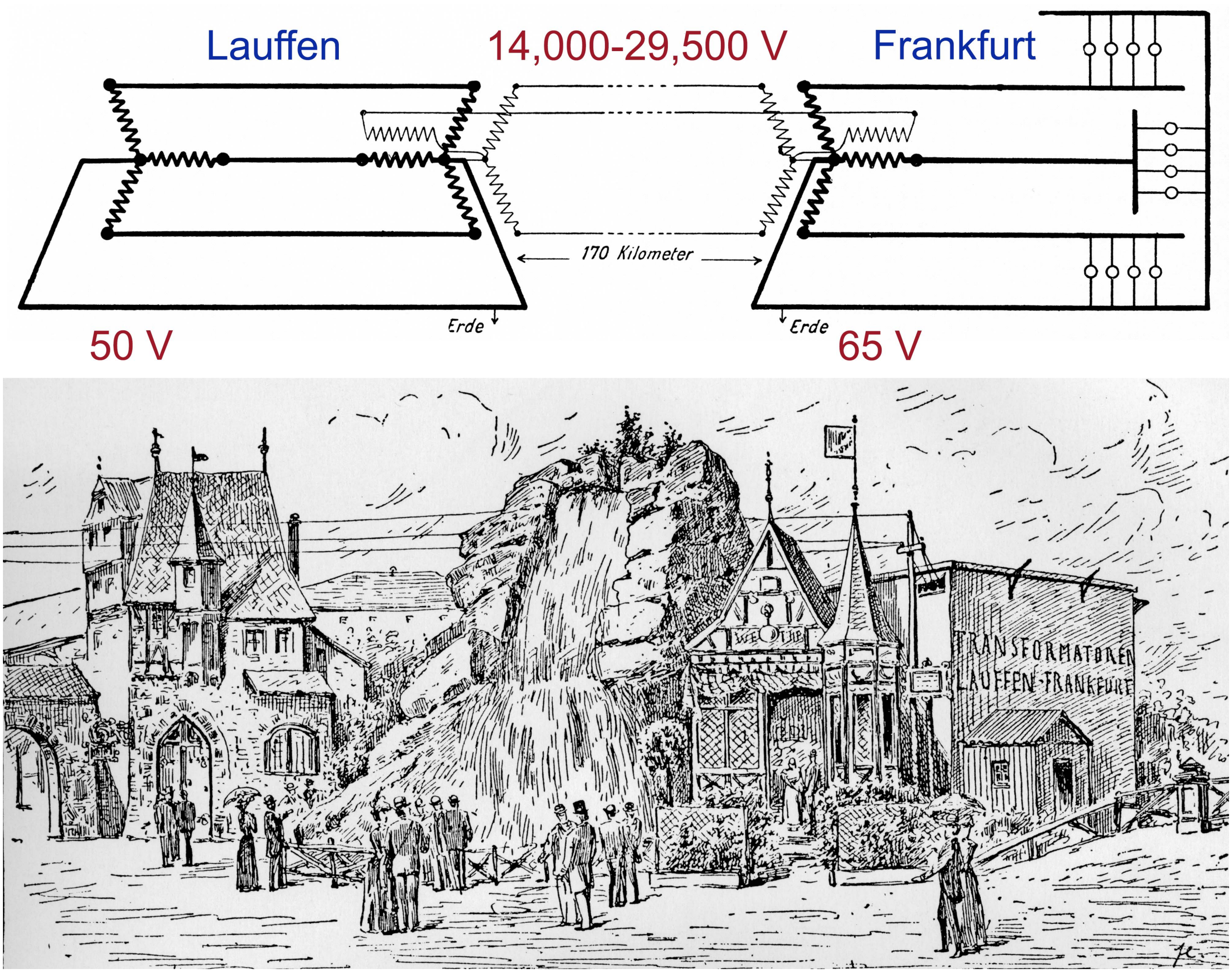

Fig. 6. *(Top) Wiring diagram of the Lauffen–Frankfurt transmission system, adapted from [22]. (Bottom) Artificial waterfall at the Frankfurt end of the Lauffen–Frankfurt transmission line, driven by a pump powered by an electric motor. Illustration from Kleine Presse (Frankfurt) of September 11, 1891.*

transmission system was designed and built by ASEA. ASEA was formed in 1891 by the merger of Elektriska aktiebolaget i Stockholm with Wenströms & Granströms Elektriska Kraftbolag, the latter cofounded by Georg Göran Wenström, brother of Jonas [48], [49].

Jonas Wenström (see Fig. 8) was born in 1855. He was affected by rickets as a child, which weakened him for life. He studied at the University of Uppsala and later at Kristiania University in Oslo, where he received a degree in science in 1879. The ASEA story begins with a visit by 26-year-old Wenström to the 1881 International Exposition of Electricity in Paris, where he examined dynamoelectric machines. In 1882, he built his own dc generator and used it for a public demonstration of electric lighting. Also in 1882, he patented in Sweden and six other countries a method for improving the efficiency of dynamoelectric machines by embedding the wires of the armature in slots [50],[6] [51], which became the standard practice worldwide. Wenström's dc generator was noticed by entrepreneur Ludvig Fredholm, who decided to form a company that would build generators and motors based on Wenström's patent. With other investors, he founded Elektriska aktiebolaget i Stockholm in 1883. Georg Wenström was appointed as the Chief Engineer. Jonas Wenström agreed to sell patent rights and be a technical advisor to the company, in return for some shares and a cash payment [48]. He became, at the age of 28, the technical driving force for the creation of ASEA eight years later. Wenström's illustrious career in electrical engineering was tragically cut short at age 38 by pulmonary disease just as the Hellsjön–Grängesberg transmission system became operational.

Elektriska aktiebolaget i Stockholm built dc generators and motors of various sizes. It started out with seven employees and delivered 16 machines with an average capacity of 62 hp each in 1883. Wenström's second dynamo design was introduced in 1887. The number of employees grew to 54 in 1890, with 36 machines with an average capacity of 500 hp sold that year. The focus of the business was the sale of machinery for electric lighting and the installation of the equipment. However, the company's successful installation of a few low-voltage dc transmission systems prompted Georg Wenström to inspect transmission

[6]As a patent of J. Wenström dated November 25, 1882, but now owned by ASEA [55].

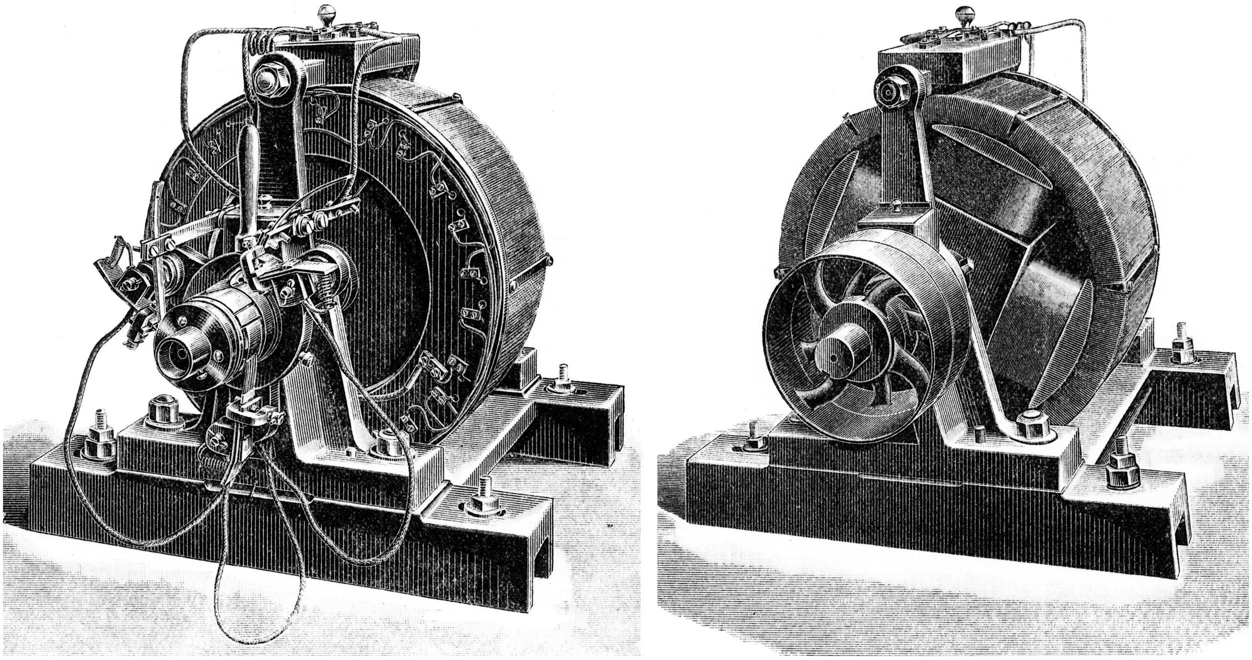

Fig. 7. ***Haselwander's three-phase generator at the 1891 Frankfurt Exposition, illustration from [8].***

installations in Germany and other countries in 1889 in order to evaluate the possibility of forming a company in Sweden that would be a "power company" partner of the "lighting company." Merchant Gustav Granström supplied the capital. His son, engineer G. A. Granström, partnered with Georg Wenström to form Wenströms & Granströms Elektriska Kraftbolag in September 1889 with the lighting company's approval [48]. The two companies merged one and a half years later due to Jonas Wenström's patent for a three-phase generator (see Fig. 9), filed on January 20, 1890, in Sweden [52] and on April 9, 1890, in Britain [53]. A notebook of Wenström's calculations and drawings in 1889–1890 related to his three-phase invention has survived. Production and testing of prototypes took place in 1890 and the spring of 1891 [46].

Fig. 8. ***Photograph of Jonas Wenström taken by his friend and collaborator Ernst Danielson. Digital image kindly provided by Prof. Sture Eriksson.***

There was hope that Wenström's three-phase invention would lead to extensive electric power transmission in Sweden. However, the fact that Wenström's three-phase patent was owned by the lighting company and that Wenström was bound by his contract to that company created the risk that cooperation of the lighting company with the power company might cease. This led to a merger of the two companies into a larger one, ASEA on February 6, 1891 [49]. The German firms Schuckert & Co. and Siemens & Halske had well-established agencies in Sweden, and a strong Swedish company was needed to prevent them from dominating the Swedish electric power transmission market. The formation of ASEA in 1891 and its subsequent quick entry into the three-phase transmission business came in the nick of time. Wenström was a first-class inventor, but his friend Ernst Danielson converted his invention into a viable commercial product. Danielson was born in 1866 and died of pulmonary disease in 1907 at the age of 41. He studied at Kungliga Tekniska Högskolan (KTH Royal Institute of Technology) in Stockholm. He was an Assistant Engineer at Elektriska aktiebolaget i Stockholm from 1888 to 1890. He then went to the United States, where he worked for Wenstrom Consolidated Dynamo and Motor Co.[7] and the Thomson-Houston Electric Company. In 1892, he returned to Sweden to replace Wenström as the ASEA's Chief Engineer and to work alongside his friend [48].

[7]The Wenstrom Consolidated Dynamo and Motor Co. held the United States patent rights to Jonas Wenström's DC patents and has no relevance to the history of three-phase power.

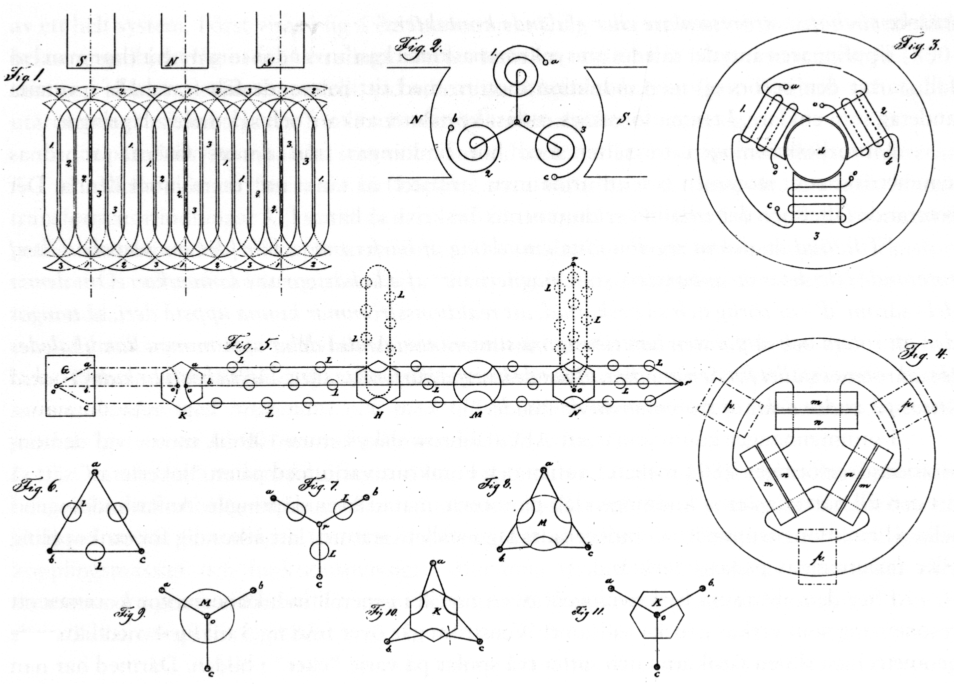

Fig. 9. ***Drawing from Wenström's Swedish patent No. 3,093 of January 20, 1890.***

The 1893 three-phase transmission from Hellsjön to Grängesberg occurred because of a serendipitous convergence of five circumstances.

1) The mine owners at Grängesberg wanted to increase production by replacing mechanical power with electric motors because of the increasing demand for steel in Europe.
2) The owner of the Hellsjö waterfall, 14 km from the most distant mine at Grängesberg, made it known in 1891 that he was willing to lease it for hydropower.

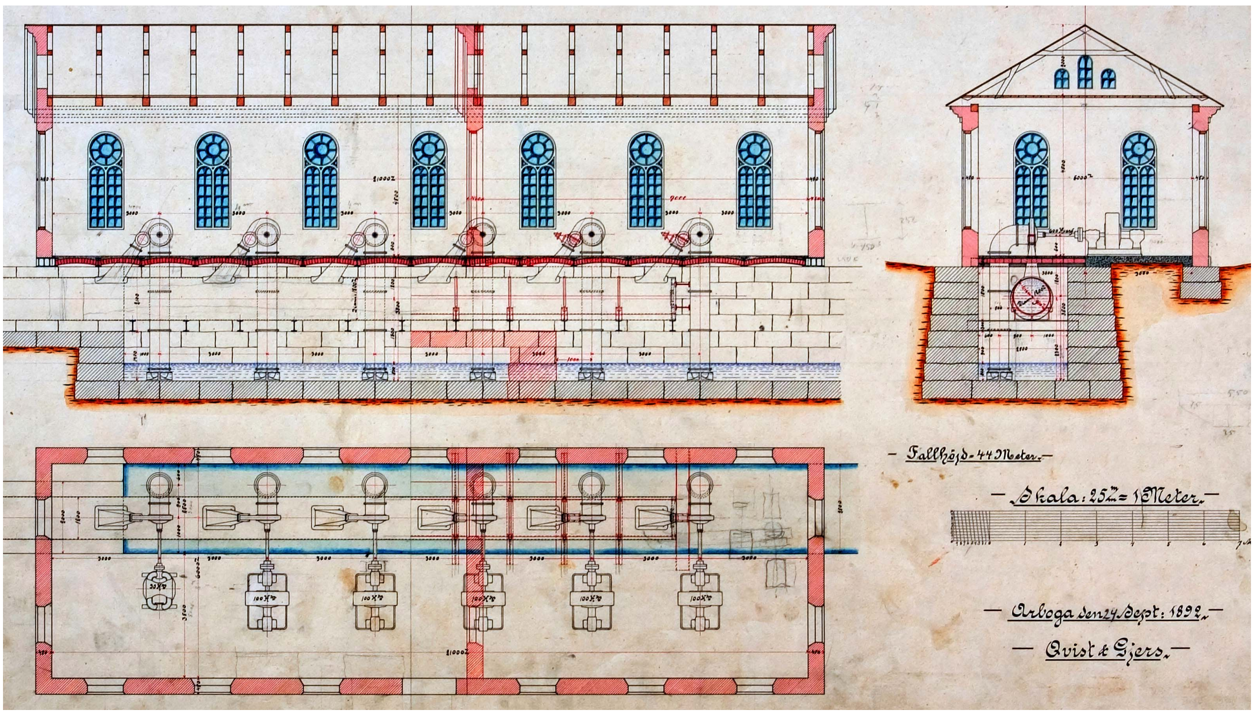

Fig. 10. ***Engineering drawing by Qvist & Gjers for the turbine system at the Hellsjön Power Station, showing five 100-hp turbines and one 30-hp turbine. The large turbines had impellers of 5-m outer diameter. Public domain image from digitalmuseum.org in Sweden.***

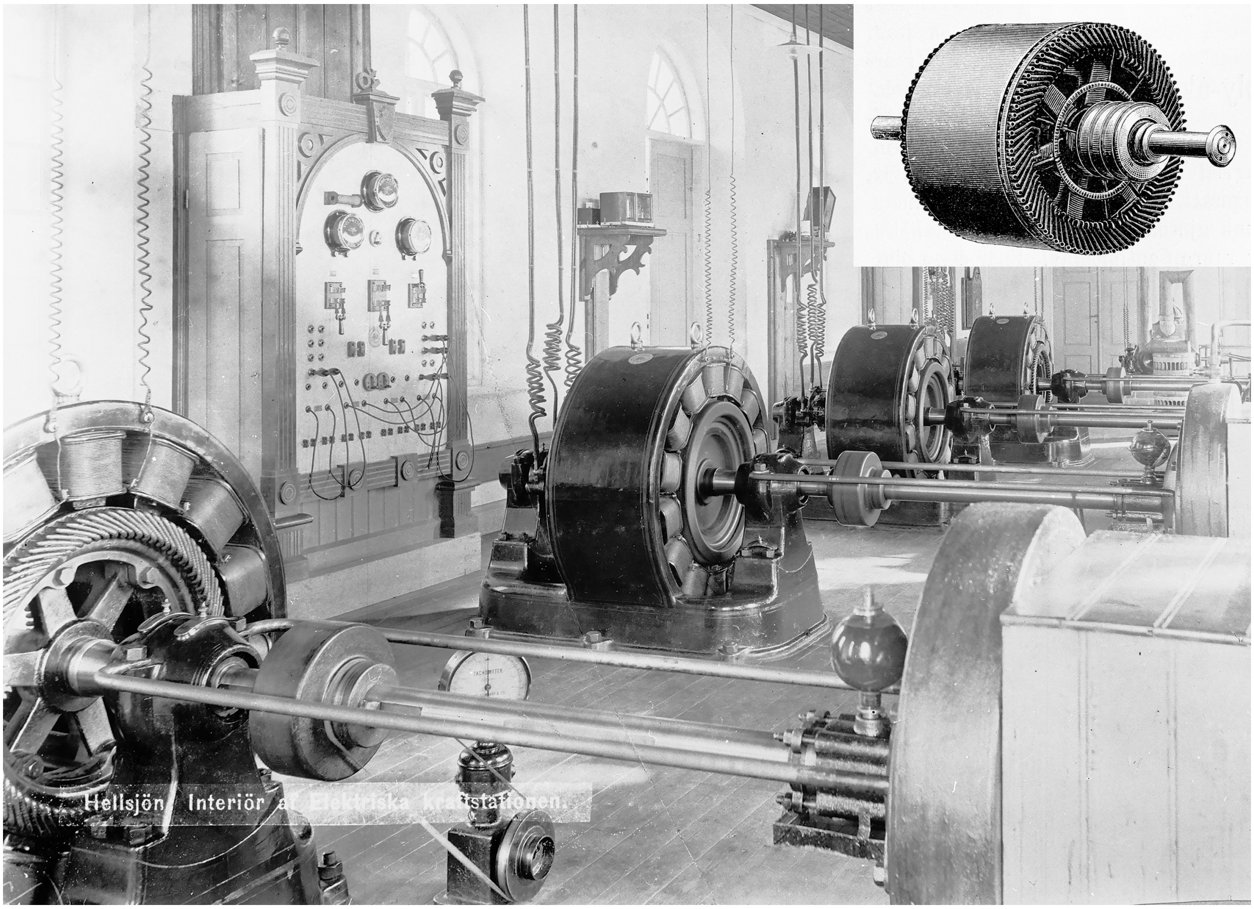

Fig. 11. *Interior of the Hellsjön Power Station. Public domain image from digitalmuseum.org in Sweden. (Inset) Ironclad armature of the 100-hp three-phase Wenström generators used at the Hellsjön Power Station [56].*

3) ASEA had installed its second hydroelectric HVDC system, 7 km at 1700 V to a silver mine, near the end of 1891 and was eager to implement three-phase transmission [54].
4) Ernst Danielson had drastically redesigned the heretofore defective Wenström three-phase motor into a successful one [55].
5) A competing Swedish firm that proposed a two-phase transmission system by German firm Schuckert & Co. came up short.

The mining conglomerate and ASEA signed a contract on January 5, 1893. The Swedish government approved the project on March 24, 1893. The prominent engineering firm Qvist & Gjers was hired to design and build the turbine system (see Fig.10). Power from three three-phase, 100 hp, 150-V (line to neutral), 14-pole, 600-rpm (70-Hz) generators was upconverted to 5000 V at the power station (see Fig. 11) and downconverted at the user end for 50-, 70-, and 85-V (line to neutral) three-phase motors. A single one-phase 5000-V line transmitted power for conversion to 110 V (line to neutral) for arc and incandescent lights [56], [57]. The inaugural transmission on December 19, 1893, did not go smoothly; there was trouble with the power cables. The transmission of power for motors was canceled through January 24, 1894, but power for lighting was not interrupted [46]. ASEA had only 170 employees when the Hellsjön–Grängesberg system was built in 1893 [58].

Jonas Wenström died on December 21, 1893. *Electrical World* (New York) of March 17, 1894, published a single-sentence obituary, right below a 22-line biography (with photo) of the treasurer of an electric utility company in Concord, NH, USA [59]. A month earlier that periodical had published a six-line snippet about the Hellsjön–Grängesberg transmission, without mentioning Wenström, ASEA, or that it was a three-phase system [60].

B. 1893 Transmission Systems of the General Electric Co. in the United States

General Electric Co. installed the first four three-phase power plants in the United States in 1893 [61], two of them began operating that year (see Table 1). Louis Bell, the Chief Engineer of the newly created Power Transmission Division, GE, was up to the task. Furthermore, the entry of GE into the three-phase power business in 1893 was facilitated by visionary consulting electrical engineer Almarian William Decker (see Fig. 12), who had designed the 45-km 10 000-V single-phase Westinghouse plant of the San Antonio Light and Power Co. at Pomona, CA, USA, which was opened in 1892 [62]. In 1892,

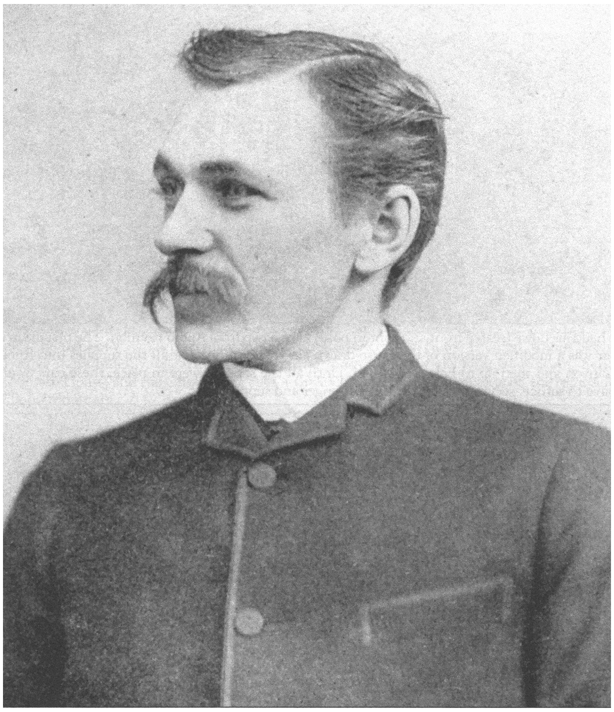

Fig. 12. ***Almarian William Decker. Photograph from [64].***

Redlands, in San Bernardino County, CA, USA, was a promising city with a population of 4500, lit solely by oil and a few private gasoline plants [63], [64]. The Redlands Electric Light and Power Co. was incorporated in the spring of that year by residents of the town "for the purpose of supplying electric light and heat for both public and private use, power for manufacturing purposes, and for the operation of street railroads in the city of Redlands and the country round about within a radius of 10 mi, such power to be developed from a transmission plant that was to be built at the mouth of Mill Creek Canyon, some eight miles distant." Hired by the company in June 1892, Decker wrote the specifications for the project. He grasped the significance of three-phase developments in Europe and included a clause requiring three-phase power, a risky move when there was no three-phase experience in the United States and even two-phase power was just emerging (see Section III). The safe bet for this short-transmission line would have been single phase because of Decker's experience at Pomona and because more than 300 central stations worldwide were using Westinghouse single-phase ac transmission at the time [65].

Decker sent preliminary plans and specifications to General Electric, Westinghouse Electric, Siemens & Halske, and the Electrical Engineering Co. of San Francisco. It took several months of correspondence before any of them would agree to submit bids. Westinghouse Electric, General Electric, and the Electrical Engineering Co. eventually submitted bids, the latter proposing an HVDC scheme of 5000-V dc generating and transmission system, with dc motors operating single-phase alternators in Redlands. Westinghouse proposed a two-phase system. Decker received only one palatable proposal. He accepted the GE proposal of two 250-kW, 2400-V three-phase generators. The built power plant contained two 250-kW 50-Hz 2500-V three-phase generators. Transformers lowered the voltage to 110 V at the user end. Two circuits ran from the power station, one to the company's office at Redlands, 12 km away, from there to be distributed for lighting and motors. The other line extended 7 km to an ice making facility in the town of Mentone. The ice was used to refrigerate shipments of fruit grown in the area. Power became available in Redlands on September 7 and in Mentone on September 13 [63]. Sadly, Decker died of pulmonary disease a month before the Mill Creek plant became operational [64], the third electrical engineer of the early years of three-phase power to die of pulmonary disease at a young age.

The generators designed and installed under Louis Bell's supervision in 1893 were still in service 16 years later [66]. By the end of the year 1895, there were more than 20 General Electric three-phase systems in the United States [67].

III. EARLY TWO-PHASE POWER

Dolivo-Dobrowolsky and Wenström had adequate financial backing; Tesla was less fortunate. In the period October–December 1887, he filed his first seven patent applications for polyphase motors, dynamos, and transmission systems, all issued on May 1, 1888 [68]. Two weeks after the patents were issued, Tesla described his invention at a meeting of the American Institute of Electrical Engineers on May 16, 1888 [4]. He sold his polyphase patents to the Westinghouse Electric Co. in July 1888 and began to work for Westinghouse in Pittsburgh. A year later, he returned to New York to begin the research that made him a celebrity [69]. Westinghouse announced two-phase "Tesla" motors and dynamos soon after acquiring the Tesla patents in 1888 [6]. Then, financial difficulties [70] delayed the implementation of a Westinghouse polyphase transmission system. The Westinghouse Electric Co., formed in 1886, had rapidly expanded. Sales income increased 30-fold

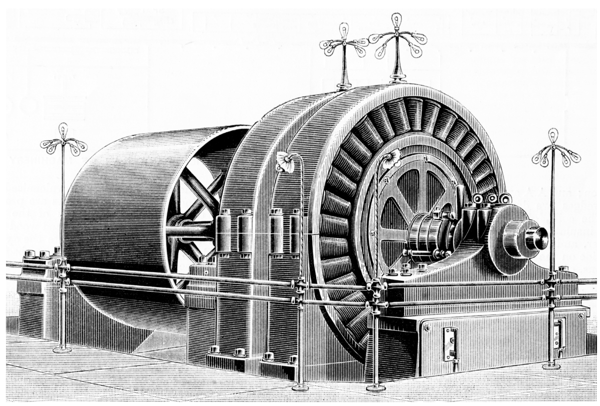

Fig. 13. ***750-kW 2000-V Westinghouse two-phase generator at the 1893 World's Columbian Exposition in Chicago. Illustration from "Electrical Engineering at the Chicago Exhibition," Engineer (London), vol. 75, pp. 565–571, 1893.***

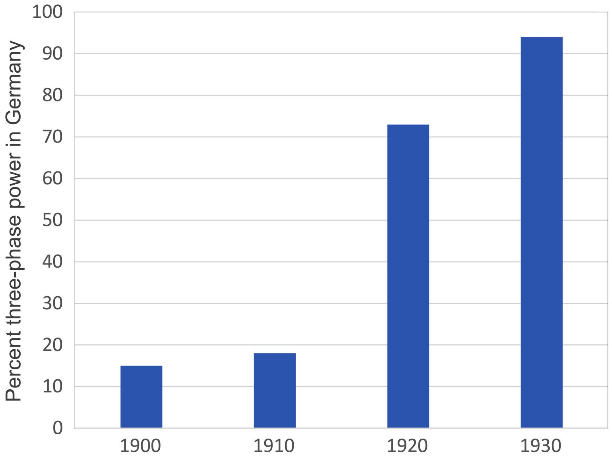

Fig. 14. ***Growth in the percentage of three-phase power in Germany. I created the graph using data from [78].***

in its first five years. The cost of expansion created a heavy debt, and it became necessary to secure the aid of a consortium of bankers. On April 23, 1891, George Westinghouse sent a letter to stockholders urging them to accept the provisions of an agreement that would extricate the company from the brink of receivership. The crisis had caused a disruption in the company's business. Recovery began when the now renamed Westinghouse Electric & Manufacturing Co. was awarded the contract to light the 1893 World's Columbian Exposition in Chicago and used massive 2000-V 750-kW "Tesla" two-phase generators (see Fig. 13) to power the exposition [7]. However, it was not the first demonstration of two-phase transmission; Schuckert & Co. had exhibited a 4-km two-phase system at the 1891 Frankfurt Exposition [8], and commercial two-phase systems of Brown, Boveri and the Stanley Electric Mfg. Co. preceded the Westinghouse demonstration. Because Stanley's patented arrangement created two magnetic fields alternating in space and not rotating [71], it was believed that Stanley's two-phase system did not infringe on Tesla's patents [72]. I am not aware of two-phase patents by Schuckert & Co. or Brown, Boveri, or any pertinent patent licensing or litigation.

Two commercial two-phase systems became operational in 1892; a hydroelectric one in Baden, Switzerland installed by Brown Boveri [38], and an experimental/commercial plant in Pittsfield, MA, installed by Stanley Electric [61]. By the end of the year 1894, the Stanley company had one two-phase system in Canada and 22 in the United States [73]. Brief reports about a Westinghouse two-phase system under construction in Washington State appeared in late 1893 and early 1894 [74], but the first commercial Westinghouse polyphase system clearly on record is the one at Niagara Falls, which began two-phase transmission to nearby industries in 1895 and three-phase transmission to Buffalo, NY, USA, in 1896 [75]. The Westinghouse company was still using two-phase generators in 1896 but was converting to three phase for long-distance transmission at Niagara and elsewhere [76] because three-phase lines can use 25% less copper than two-phase lines [77].

IV. COEXISTENCE

The relative number of low-voltage dc, HVDC, single-phase ac, two-phase ac, and three-phase ac systems in the early years of electric power varied with time and from country to country. Fig. 14 shows the growth in the percentage of three-phase power in Germany from 1900 to 1930 [78]. I could not create a similar graph for the United States because the reports of the Bureau of the Census combined single-phase, two-phase, and three-phase ac in 1902 [79], 1907 [80], and 1912 [81]. As of 1916, there were few two-phase stations left in the United States, and most large and recent power stations generated three-phase power [82].

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