Survey on Induction Heating Development in Italy

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Abstract **- This paper presents a short survey of the development of induction heating technology in Italy, seen in the frame of the international outline. The paper is based on the "*lectio magistralis*" given in Padua by the author on December 13, 2010 entitled "Research in the field of induction heating at the University of Padua" [1].**

After a short historical background, focused on the period before the WWII, the paper deals with the activities in this field of the most important Italian companies and the research developed at the University of Padua.

1 – FROM PIONEERS TO WWII

Thanks to the fundamental discoveries the pioneers of electromagnetism *M. Faraday* (1791-1867), *J.P. Joule* (1818-1889), *J. C. Maxwell* (1831-1879) and some years later to the works of *W. Siemens* (1816-1892) on the development of direct-current dynamo-machine and *N. Tesla* (1856-1943) on rotating magnetic field, alternating-current machinery, transformers and dynamos, from the middle to the end of the nineteenth century all the basic knowledge concerning electromagnetic induction, heat generation by electrical currents, AC power generation and its technical importance as well as the theoretical basis for the calculation of the electromagnetic phenomena were available to the leading scientific and engineering society around the world [2].

At the beginning, due to the availability only of mains frequency transformers and generators of sufficient power, also the induction heating started at 50 Hz/60 Hz with the development of the channel-type melting furnace, where low frequency was sufficient for heating and melting the charge.

Induction furnaces - The first known application was proposed in 1887 by *Sebastian Ziani de Ferranti (1864-1930)*, a very talented English electrical engineer, who constructed his first dynamo when fourteen years old and, at about seventeen years, made a series of experiments at Kings College on electric furnaces for Sir William Siemens at the *Siemens Brothers & Company*, at Woolwhich[1]. He patented his invention in 1887. [3]

The furnace was constituted by a magnetic circuit with a coil wound around the central limb and an oval annular channel of non-conducting material, in which metals could be melted; by using a metal through, water or other liquids could be also heated (*fig. 1)*.

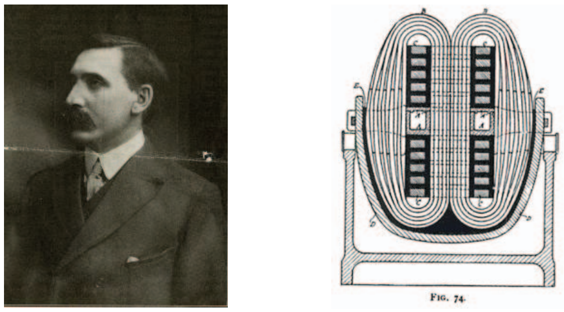


Fig. 1 *Ziani De Ferranti and his induction furnace – 1887*

But this type of furnace became usable in industrial application only after the improvements and experiments made from 1891 to 1900 by *F.A. Kjellin.*

In fact, on February 1900 the first industrial furnace for steel melting was installed in Gysinge, Sweden, and patented in the same year. [4] As shown in *fig. 2*, the furnace was designed as a single-phase AC transformer, in which the inductor acts as the primary winding and the channel containing the melt as a single secondary winding, carrying the induced current. Between 1900 and 1901 two other furnaces were constructed increasing the capacity from the 80 kg of the first one to 180 and 1800 kg, improving the design and reducing the energy consumption from the 8.000 kWh per ton of the first furnace down to 800 kWh per ton.

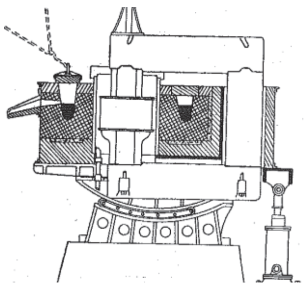


Fig. 2 - *Kjellin furnace – 1891*

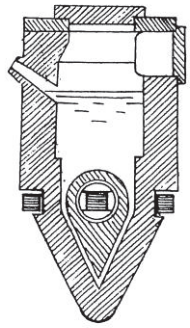


Fig. 3 - *Ajax-Wyatt furnace – 1915*

In order to overcome the limitations of the Kjellin furnace design, i.e. the break off of the liquid metal at high power levels and the high thermal losses, the American engineer *J. R. Wyatt* proposed in 1915 a V-shaped channel in a vertical plane below a cylindrical crucible, *fig.3***.** In this design, the hydrostatic pressure of the melt, acting against the pinch-effect, gave the possibility to increase the furnace power. This design, with modifications and improvements, is still

[1] The Italian name Ferranti comes from his Venetian father Cesare.

used in line-frequency channel induction furnaces for melting and holding ferrous and non-ferrous metals.

After the findings in the years 1895-1897 of the Russian *A. Popov*, the Italian *G. Marconi* and the Croatian *N. Tesla*, various scientists began to investigate on wireless transmission methods and to develop different types of HF generators (spark generators and motor-generators), for stable radio frequency transmissions.

At the beginning of the 20th century, the studies on these HF power sources suggested the development of the coreless induction furnace, where the use of exciting currents at frequencies above the mains one allows to increase the power induced in the charge without the need of a magnetic core.

The first patent for a furnace of this type is attributed to the *Soc. Schneider Creusot* (1905), where an “Electric induction furnace for high frequency currents”, supplied at 100 kHz is described; but there are not information on the practical realization of this patent.

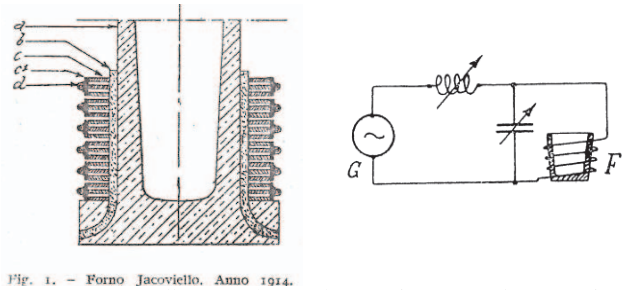


Fig.4 - *Jacoviello coreless induction furnace and power factor compensation scheme*

Some years later, the Italian professor *Felice Jacoviello***,** University of Parma, in an Italian patent obtained in 1914 described a coreless furnace at a frequency of 400 Hz [5]; moreover, he first proposed to compensate the reactive power by capacitors, according to the scheme of *Fig. 4*.

It’s interesting to quote here the claims of this patent:

1. construction of an (induction) furnace (at high frequency) similar to a transformer without magnetic core;
2. utilisation of a frequency above 400 Hz, which can be easily produced with industrial alternating current generators;
3. utilisation of electrostatic capacitors for reaching a unity power factor,

since the described connection scheme and design features are very similar those used up to now in industrial furnaces.

Many scientists and engineers in USA, Europe and Russia continued to push forward the development of high frequency furnaces. I can mention in this short historical overview only the two most important of them.

- *Edwin F. Northrup*, (1866-1940), (*fig.5),* professor of physics at Princeton University, designed in 1916 the first HF crucible furnace, powered by a 20 kHz spark gap generator. In several publications from 1919 to 1921 he described the principles of induction heating of metals with high frequency currents [2].

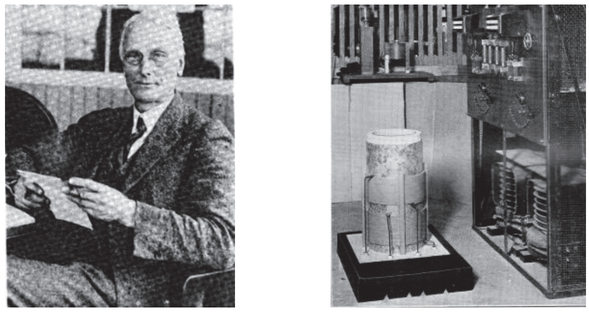


Fig.5 - *Edwin F. Northrup and his20 kW HF furnace*

- *Valentin P. Vologdin* (1891-1953), professor at the engineering faculty of St.Petersburg (Russia), has given outstanding contributions to the development of HF power sources and applications of induction heating and melting.

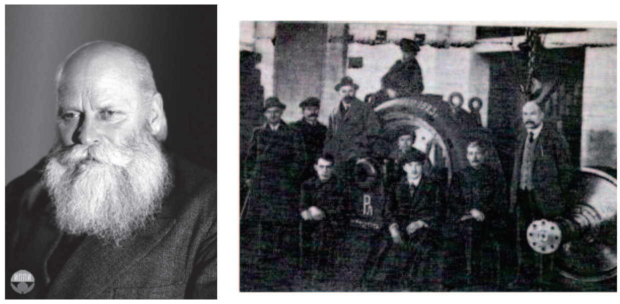


Fig.6 - *V.P. Vologdin and his group in the Nizhegorodskaya Radio Laboratory with a generator 150 kW, 15 kHz, 1923*

Since 1912, he developed and built high frequency machine-generators, for wireless communication. From 1919 to 1923 he put into operation several machine-generators, 3 to 150 kW power and frequency 15÷20 kHz *(fig.5)*. This kind of power sources were the prerequisite for the development of larger high frequency furnaces. In fact, in 1926 Vologdin started investigations on large core-less HF induction furnaces for the melting of non-ferrous metals and steel alloys, sourced by machine-generator sets.

Some years later he developed and used high frequency vacuum tube generators instead of rotating machines for high frequency applications [2].

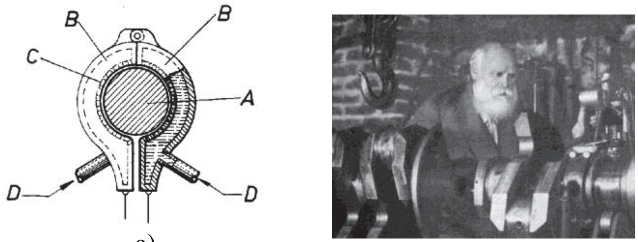
The theoretical developments carried out in many countries by many scientists and engineers, and the successful implementation of their results into the industrial practice marked the beginning of a wide practical use of the high frequency induction heating technology in the middle of the 1930s.

At that time the theoretical basis for design of the melting channel and coreless furnaces was sufficient for building in next two decades larger furnaces with technical improvements like higher power densities, new refractory materials, new mechanical and electrical equipment of installations; but the main theoretical and design base remained almost the same for about 20 years.

The research activity then shifted to other induction technologies, i.e. Surface Hardening in the middle of the 30s and Mass Heating in the 40s.

Surface hardening - Initially, the introduction of surface hardening into the industry was slow because of lack of powerful high frequency generators and insufficient knowledge about the metallurgical results of hardening. The situation changed in early 30s when induction hardening of crankshafts was first developed. In turn, this success stimulated production of new more powerful motor-generators and vacuum tube oscillators.

In 1932, the *Ohio Crankshaft Corporation (TOCCO),* a manufacturer of diesel engine crankshafts in the USA, started the first high production application of induction surface hardening using motor generators at 1.92 kHz and 3 kHz for the surface hardening of crankshafts. A special single-turn inductor was patented by *F.F. Deneen* and *W.C. Dunn* from TOCCO in 1933 [2]; it allowed to heat up the rim zone of the crankshaft and to quench it as well (*fig.7-a*).



a) b)

Fig. 7 – a) *TOCCO inductor [A-journal to be hardened; B-half-cylindrical cheeks; C-spraying nozzles; D–quench];* **b)** *Prof. Vologdin in the hardening department of LETI (1940)*

In Russia, professor *V.P. Vologdin* first obtained in 1936 two Russian patents in surface heat treating [2]. The first patent was for induction hardening of railroad rails, the second one for crankshaft hardening *(fig. 7-b).* After these successful developments, professor Vologdin continued R&D-work on surface hardening of different steel parts, including gears, camshafts etc. mainly for automotive, tractor and later military industry.

Mass Heating **-** It is difficult to find the chronological roots of the idea to heat by induction metal parts before hot forming. However, after the works of *Dr. E. Northrup*, at the end of the 20s was already proven that relatively low frequency (1-10 kHz) could be used for through heating; with the introduction of powerful and reliable motor-generators, this technology was ready for industrial use. However, the real industrial application of through heating of metals started only at the end of the 30s, mainly for economical but not technical reasons.

In 1937, the *Ajax Electrothermic Co. (USA)* put in operation two installations for through induction heating.

The first one was for heating the ends of steel tubes before hot forming: high frequency power at 2 kHz was used for heating 6 inch end sections to 1200 °C in less than 1 min.

The second application was the heating of the tube ends prior to forging. Large steel tubes, 125 mm diameter and 12 mm wall thickness, were heated in a multi-turn coil, excited at 2 kHz (figure 8).

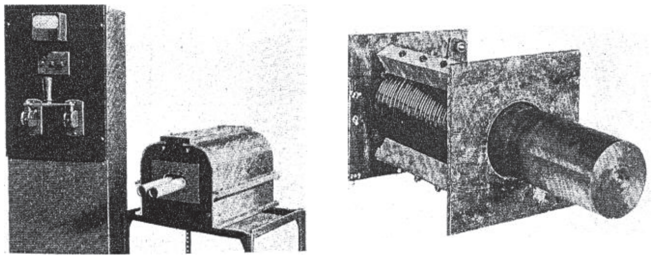


Fig. 8 *–Ajax installations for through heating and tube heating (1937)*

From 1937 to 1944 several heating plants were installed by the *Swedish company ASEA* in Europe and the *General Motors Corporation* in USA. During the WWII, induction forge heating was used in the USA, England, Russia and Germany in mass production mainly of military parts.

However, the large diffusion of the induction through heating of bars and billets took place only in the 50s, due to the rapid development of the automotive industry in all industrialised countries.

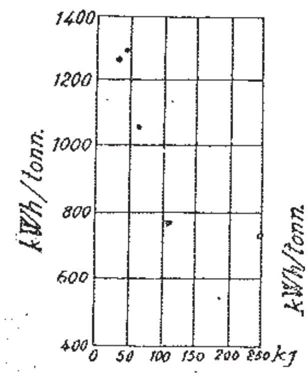
In Italy – After those on the innovative ideas of prof. Jacoviello, very few information are available about the industrial use of induction heating in Italy.

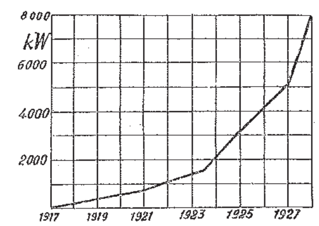
Until 1920 only the new induction melting furnaces and their comparison with the arc furnaces, predominantly used at that time for steel production, are mentioned in the literature. [7]

An increased interest for the coreless induction melting furnaces in the period 1920-1930 is testified by the papers of *L.A. Finzi,* where the developments and the diffusion of this technology is analysed in deep. [8,9]

An idea of the possibilities of induction heating and its diffusion in this decade can be obtained from the diagrams of figures 9; figure 9-a) shows the average energy consumption as a function of the furnace capacity for melting scrap iron, while figure 9-b) gives the total number of installed kW up to 1930.

a)





b)

Fig.9 – ***a)*** *Average energy consumption in coreless induction furnaces for melting scrap iron;* ***b)****Total installed kW up to 1930*

A comprehensive compendium of experimental technical data of numerous induction coreless steel plants located throughout the world is provided in the work of *L. Bemporad*; they give an idea of the progress made by the major producer companies in the period 1930 -1947 [10].

In particular, in the paper are first mentioned Italian installations at the *Società Metallurgica Italiana (1941),* the *Fonderie Mil. Acc. Vanzetti (1947), Acciaierie Cogne (1947)* and Italian producers of frequency converters, i.e. the *Tecnomasio Italiano Brown Boveri* and the *Società Italiana Costruzioni Elettromeccaniche Pellizzari*. (Table I)

Table I [10]

Date of installation	Capacity kg	Power kW	Frequency Hz	Plant
Oct. 1941	600	300	1.000/1.200	Soc. Met. Italiana
June 1947	1.500	550	-	Fond. Acc. Vanzetti
June 1947	10.000	2.500	500	Acc. Cogne Pellizzari

In fact, only the increase of the steel production due to the needs of World War I and the subsequent reconstruction required to the Italian industries to produce qualities and quantities of steel not produced before, forcing them to use electric furnaces. This is the reason of the late introduction in Italy of big capacity induction furnaces and the rising interest for the other industrial applications of induction heating.

2 – IN ITALY AFTER WWII UNTIL 2000

The development of electrical applications in general, and induction heating in particular, after the WWII is also related to the fact that in those years the only source of energy available for the Italian industry was the electric energy, because of the shortage of liquid and solid fuel.

Moreover, the rapid development also in Italy of the automotive industry produced the birth of several Italian induction heating companies in the period 1945-55.

The company *S.A.S. Calamari Elettrometallurgica* was founded in Milan in 1944; its production began with the realization of a particular type of induction furnace suitable for small and medium foundries. In the following 30 years the company has produced a wide range of electric industrial furnaces. In this period the company has installed in Italy and abroad more than 1.000 melting installations of different types and capacities.

The company Calamari in 1950 absorbed the company *C.E.T. (Electro Thermal Constructions)*, in 1964 the *CEMA (Electro Mechanical and Analogous Products Co.)* and in 1970 the *New S.p.A. Tagliaferri Furnaces*.

The company Calamari has contributed particularly to the development of the induction channel furnace at mains frequency, introducing innovations in its design and making it suitable for melting nearly all metals and alloys for applications in any kind of foundry.

For the foundry of ferrous metals in 1952 Calamari has introduced a special furnace design, so-called with oscillating channel, for temperatures up to 1650 C for the melting of inox and carbon steels; however, most widely used was the coreless type furnace (figure 10).

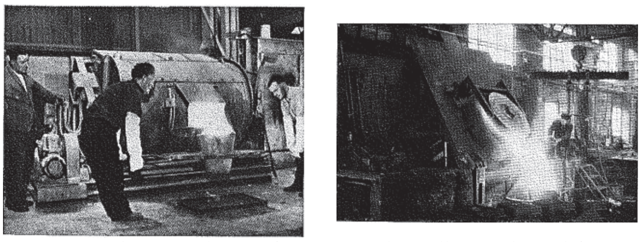


Fig. 10 – *Calamari induction furnaces: with oscillating channel for inox steel melting (left); coreless for cast iron (right)*

Among the other manufactures of induction melting furnaces we should mention *CIME Crescenzi S.r.l.,* founded in 1952, who introduced a special design furnace, named CAP – Coreless Automatic Press-Pour, featured to melt, overheat, allow rapid change of melting alloy, maintain of the melt at constant temperature and coupled to an automatic casting pressure machine , which is essential for casting ductile cast iron, and the other company *FOMET,* founded in Milan in 1963.

The first years after the WWI have also seen an increasing interest for all other induction heating applications. The main center of this interest was Padua, where a deep research activity was initiated and developed at the University by the emeritus *Prof. Ciro Di Pieri* (Fig. 11).

In 1931 he graduated at the University of Padua and started his activity at the Institute of Electrotechnics.

From 1943 he oriented his research on frequency converters (see fig. 12), medium and high-frequency heat treatments and, in general, all induction heating applications. [1,11]

Fig.11 - *Prof. Ciro Di Pieri (1908-1996)*

He dedicated his scientific interest not only to the theoretical research but also to industrial realizations as technical director, in Padua, of the company *SIATEM - Società Italiana Apparechiature Termo Elettromeccaniche,* establishing a very close and fruitful link between university and industry.

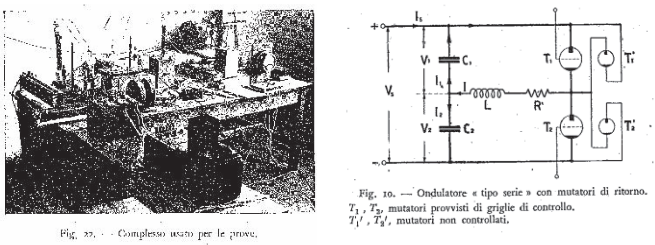


Fig. 12 – *Mercury valve converter for power supply of high frequency furnace (1943)*

Among his collaborators in this field mention must be made of *L. Merigliano* and, from 1962-1964, *A. Morini* and myself.

An important step forwards for the research activity was made by *prof. Di Pieri* in 1969 with the foundation of the "*Laboratory of the Institute of Electrotechnics and Electronics of the University of Padua for researches and tests in the field of induction heating and hardening";* the laboratory was equipped with a 100 kW motor-generator at 9800 Hz and a 90 kW HF generator at 450 kHz [1].

After the death of prof. Di Pieri, the activity of the laboratory continued under my the supervision of till his my retirement (in the year 2010), with the fruitful and clever collaboration of *Fabrizio Dughiero* and *Michele Forzan*.

This laboratory is presently known as ***LEP* – *L*aboratory** *for* ***E****lectroheat of* ***P****adua University* and has available modern test facilities and calculation means.

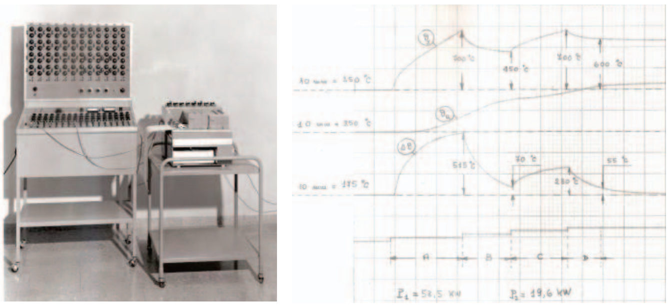
Although since 1963 were developed the first FD numerical solutions of induction heating problems, a 1-D coupled electrical and thermal calculation of the heating of ferromagnetic cylinders and a 2-D solution of the induced current distribution in a short cylindrical non-magnetic body [1], nevertheless till the end of the 70s - beginning of the 80s, numerical simulation did not become a widely used tool for research and design due to the lack of sufficiently powerful computers.

Therefore before the 80s current research means were experimental tests combined with analytical calculations.

Some interesting examples of the results obtained at LEP with these techniques are the following:

- Design of induction lines for billets or bars heating - one actual problem in the 60s was the evaluation of the temperature distributions in billet heating lines for forging applications, where the technological requirement is to achieve a final limited temperature difference in the billet cross-section.

Since computers were not available at that time, the problem was solved by a special Beuken model (Fig. 13-a), in which a R-C network was supplied with currents reproducing the radial induced current distribution in the cylinder at different stages of the heating transient. An example of the results given by this model is shown in Fig. 13-b), where the surface and axis transient temperature distributions in a two stage heating are shown. [1].



a) b)

Fig. 13 - *Beuken model for analysis of heating transients in a two-stage induction heating of a cylindrical aluminium billet*

From the beginning of the 80s, with the availability at LEP of the first PCs, the calculation of these lines, was performed with an *ad hoc* developed numerical programme, very flexible and fast, which has been used since then on for the design of many different installations, e.g. for hardening and tempering of steel bars, also in connection with numerical optimization procedures. [1]

- ***Analytical calculations of inductors with multiple coils***

In the middle of the 70s in the Italian Universities the first computers with sufficient memory became available and some activity was devoted to improve the calculation of series-based solutions proposed in previous times.

The first work of this type developed at LEP is the paper *"Calculation of the induction heating of cylindrical rods"*. Similar developments were done in the same years by the Canadian *J.D. Lavers* and *P.P. Biringer*. [1]

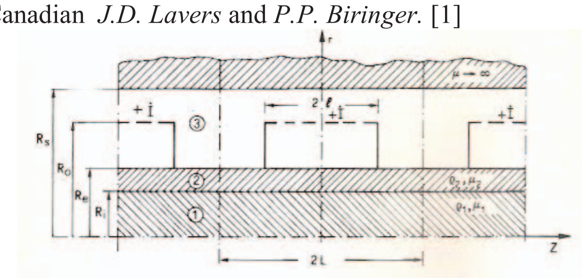


Fig. 14 – *Scheme of inductors with periodical fields*

In the same period, in 1974, arrived at LEP from the Institute LETI of St.Petersburg as young visiting scientist, *prof. Valentin Nemkov,* the grand-son of prof. V. Vologdin, and we started a fruitful scientific cooperation and a sound and long friendship. Two years later (1976), I reciprocated the visit at LETI in St. Petersburg working for some months at the chair of *prof. A. Slukhotsky.*

Joining the previous experiences of LETI in the calculation of sectionalized inductors and that of LEP in the calculations of inductors with periodical fields, this cooperation produced a number of papers related to the analytical calculation of induction heating systems of the type sketched in fig. 14, with single or multiple coils of any length, with internal or external loads, solid or bimetallic, with or without magnetic yokes. [1]

Induction pulse hardening - In 1981 Alfa Romeo commissioned to *Siatem* a research for the development of a prototype for pulse induction hardening of crankshafts and LEP cooperated in this research with theoretical analyses and tests.

The hardening tests were performed with power pulses obtained by means of a capacitors-discharge high-frequency generator at 450 kHz, as illustrated in fig. 15; HF oscillations were produced, characterized by envelope curves to the peaks which followed the same transient distribution as the discharge current of the capacitor's bank.

The process was characterized by high-frequency peak power densities (from some kW/cm^2 up to 10÷20 kW/cm^2), by heating times in the range from tens to hundreds milliseconds and by the fact that the cooling rate required to stabilize the grain structure was attained by self-quenching.

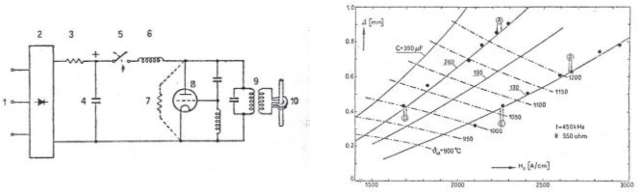


Fig. 15 - *High-frequency pulse induction hardening [left: schematic of the pulse generator; right:hardened depth, HF magnetic field intensity and maximum surface temperature for different capacity of the capacitor's bank (• - experimental points)]*

The knowledge of the transient temperature distribution during heating, carried out with a 1-D numerical *ad hoc* model, allowed to predict the so-called "austenitisation depth" defined as the depth Δ to which the temperature at the end of the heating transient is equal to or higher than the austenitisation temperature of the material.

The experimental work confirmed a fairly good agreement with the theoretical prediction as indicated, as an example, by the results given in Fig. 15.

From the beginning of the 80s till the present days, the availability of computers with continuously increasing capabilities allowed to implement ideas presented since long time, but which were not put into practice because good design was not possible only by try and test methods.

- This is the case, for example, of the project developed by LEP in 1987 in cooperation with *Siatem* in the field of the ***"Single-shot Induction Hardening of Ring-gears"*** (Fig. 16). A very old proposal and experimental data were available since the 30s after the works of prof. Vologdin, but the real optimisation of the process became possible only by the use of numerical calculation methods.

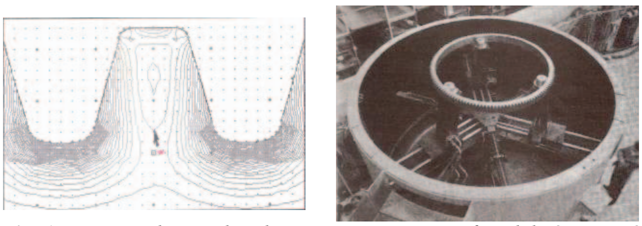


Fig. 17 - *Power density distributions in ring-gear of module 8 mm at 8 kHz (left) and heating machine Siatem for single-shot hardening of large ring-gears*

The experience done in this field was useful later in the years 2005-2010 when studying the simultaneous dual frequency (SDF) technique in cooperation with the German company *Eldec-Schwenk Induction GmbH.*

- Another successful research project was developed in the years 1992-95 on ***"Transverse Flux Induction Heating (TFH)"*** of non-ferrous or stainless steel strips. This idea was already available from the 50s; but without a full coupled 3D electromagnetic and thermal calculation, which became possible only in the last 20 years, it was practically impossible to obtain the required heating uniformity.

A Joint European Project developed by the Institute ETP of the University of Hanover, the laboratory LEP of Padua and German and Italian industrial partners, allowed to optimize the design of industrial TFH installations, e.g. a 10 MW–1000 Hz plant built in Germany by *SMS Elotherm* in cooperation with ETP and a 600 kW-3kHz installation built by the Italian company *ATE* and designed in cooperation with LEP (fig. 17).

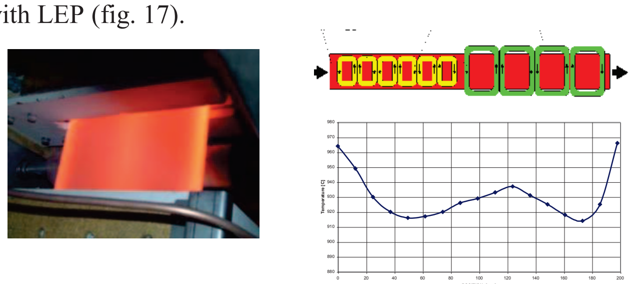


Fig. 17- *600 kW installation for austempering of magnetic steel strips: scheme of inductors and temperature distribution in the cross-section*

It is impossible here, because of the limited space available, to mention all the activities developed from the 50s at LEP and by the numerous Italian companies active in the field of induction heating. This is why I have stopped this short overview at the 90s.

As regards LEP, more detailed information can be found in [1]. As regards Italian companies, mention must be done of the activities in the field of induction furnaces of *TAGLIAFERRI Italia*, *FOMET Italia*, *Elettro-Metallurgica CALAMARI* and of *SIATEM*, *SAET, IVET, ELIND* and *ATE* as producers of induction heaters and induction hardening installations.

Finally, I would like mention the fruitful international cooperation of LEP with the *Institute ETP of the University of Hanover (Germany),* the *Electrotechnical University LETI of Saint Petersburg (Russia)*, the *State Technical University of Novosibirsk (Russia)* and the *State Technical University of Samara (Russia)*.

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