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Tesla's Polyphase System and Induction Motor

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1 Introduction

While new scientific knowledge is acquired by learning, observation, experiments and thinking, the inventions are mostly the fruit of the intuition of individuals and of their creative impulses. Inventors are people who use consciously or unconsciously the accumulated human knowledge and experience, and find useful solutions for the humanity. Some of those inventions are epochal, like for instance the inventions of the steam and the internal combustion engine. These epochal inventions obviously include the Tesla's system of polyphase alternate currents and Tesla's induction motor.

It can be often heard that in some eras of civilization there appear needs and there ripen circumstances for the appearance of great inventions. The sequence of the human acquisition of knowledge of natural phenomena on which the function of the induction motor is based, and the sequence of experiments in the attempt to make the induction motor show that that opinion is not without basis. In the following lines, we will tell the story of the induction motor. That story will not be limited to Tesla's key contribution only, but it will mention things that happened before and after Tesla's patent applications by the end of 1887.

2 Discoveries

The induction motor rotates thanks to the natural phenomenon which may be described by the following words: the moving magnetic field of one part of the motor, for instance the stator, induces currents in the conducting parts of another part of the motor, the rotor. Between the magnetic field of those induced currents and the moving magnetic field, there appears a mutual action, resulting in the fact that the parts of the machine in which the moving magnetic field is being created attract the parts of the machine in which the electric current was induced, creating by that an mechanical torque.

The discovery of that natural phenomenon happened by the beginning of the nineteenth century. The constructors of compasses, sailor's compasses, noticed that the kind of support on which the pivot is mounted influences the oscillations of the magnetic needle. The phenomenon was described in 1824 by the Paris

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constructor of instruments Gambey, and the French astronomer Arago presented in the same year in the French Academy of Science a work in which he presented data about the oscillations of the magnetic needle above wood and copper supports. In the next year, he made the well known apparatus which consisted of a magnetic needle below which a copper disk was rotating. At small rotating speeds, the needle deviated at an angle proportional to that speed, and when the speed was high enough, it rotated in the same sense as the copper plate. That phenomenon was called the rotation magnetism and it was mentioned during decades in textbooks of physics. Concluding quite rightly that the law of action and reaction must be valid in that phenomenon as well, Babbage and Herschel constructed a device in which, under a copper plate mounted on a pivot, there rotated a permanent magnet in the form of horseshoe. By rotating the magnet they created a rotating magnetic field which towed the copper plate and made it rotate in the same sense as the rotation of the magnetic field. Those phenomena were studied by many scientists of that time. Therefore, it was discovered, in the third decade of the nineteenth century that a copper plate rotates in the rotating magnetic field; that was the discovery of a natural phenomenon which will be used, many years later for the construction of the best electric motor.

3 Knowledge

The scientists were not able to describe quantitatively the laws of nature which would explain the Arago's rotating magnetism. Moreover, they explained wrongly that phenomenon by Coulomb forces, believing that the copper was temporarily magnetized. Only after the discovery of the law of electromagnetic induction, in 1831, and after the introduction of Faraday's notion of magnetic lines, satisfactory explanations of that phenomenon were given.

Faraday and other physicists came to the conclusion, by mid-nineteenth century, about the unity of electric and magnetic phenomena, about their dynamic connection. Maxwell, the follower of Faraday, translated all existing knowledge and experience of his contemporaries into several mathematical equations, which got eventually his name. Those Maxwell's equations describe completely the electromagnetic phenomena and represent a unique monument to human capability to describe, by several symbols and mathematical relations, quite complex laws of nature. Today, Maxwell's theory of electromagnetism is indispensable for the complete understanding of the function and of the construction of devices and machines of classical electrical engineering. In the nineteenth century, however, it was little known by the engineers and the inventors of electric devices.

4 Inventions

In real life, we seldom meet inventors who are equally gifted for theoretical-mathematical thinking and physical-practical understanding. Most often it happened that inventors, even those who are most important for the development of civilization, were not, at the same time, the best theoreticians of their time. Maybe inventions are rather the result of chaotic than of systematic thinking. Maybe the scientists' strictness and severity hamper the imagination of the wisest people.

Hoping that we will not be wrongly understood, we will mention, three quotations connected to that problem, quotations expressed by people of highest knowledge, wise people who deeply respected the capability of their contemporaries to think and create in their own peculiar way.

"...The absence of complex analytical formulas often makes easier the concentration for the physical understanding of problems, for more lively observation and better understanding of the substance, than when the electric phenomena are viewed through the clouds of mathematical symbols", Sir J.J. Thompson, *"Elements of the Mathematical Theory of Electricity and Magnetism"*.

"... Ignorance contributes much more frequently to self-confidence than knowledge", Charles Darwin, *"The Descent of Man"*.

"...Make it possible to them to invest effort and to express their ideas by words, without the use of symbols, and if they succeed in doing so, they will show to us that we are incapable, and they will enthusiast themselves during the explanation, and they will even doubt that the ideas expressed may ever find the way out of equations" James Clark Maxwell, *"The Scientific Papers."*

These quotations were mentioned primarily in order to shed light on the specially gifted men – the inventors. The first quotation tells us that sometimes it is possible, without completion of schooling, without the knowledge of high mathematics and theoretical physics, to understand the natural phenomena and to create. The second quotation explains the fertile self-confidence, but often also the fascination with the idea which the inventor can not evaluate objectively, as well. The third quotation speaks about the special talent of some people to see things which the majority of their contemporaries can not understand without relying on mathematical formulas. Maxwell's quotation concerns the exceptional people who are capable of understanding and explaining some phenomena, in accordance with scientific truth, without the usual theoretical and mathematical justification. Our Great Man, Nikola Tesla is a typical example of such person.

Regarding the debate, which lasted almost during half a century, about the primacy for the invention of the induction motor, let us mention the following facts.

Babbage's and Herschel's apparatus for the demonstration of rotating magnetism and of the rotation of the magnetic plate is not the predecessor of the induction motor, but the hint of the natural phenomenon which is the basis of the function of the induction motor. In that apparatus, mechanical rotation is obtained from mechanical rotation, therefore it is a kind of rotating induction clutch.

It may be said that the predecessor of the induction motor is the Bailey's apparatus in which the alternate switching off and on of the current in four coils results in the progressive movement of the magnetic field which induces the rotation of the copper plate which is placed above those electromagnets. This invention was shown by Bailey in the London Physicists' Society on June 28th, 1879. Tesla knew about that Bailey's invention and mentioned it in his patent application of October 12th, 1897.

It is true that in Bailey's apparatus polyphase currents which flow through the spatially shifted coils are created, which creates a rotating magnetic field. However, Bailey's apparatus can not be called a practical invention of induction motor, due to the following reasons. First of all, the obtaining of polyphase currents by switching direct current off and on by a mechanical switch provokes big losses of energy, and, secondly, that switching of current produces impermissibly strong sparking which destroys the contacts of the switch. Bailey described correctly the phenomenon of induced currents in the copper plate, the rotor of his apparatus, and understood how, in accordance with the electromagnetic theory, mechanical torque which makes the copper plate rotate, is created. He was, at the same time, quite conscious of the fact that his invention is not the invention of a practically usable electric motor. Very modest, when one present professor asked him jokingly what power may be created by his motor, he answered that, for the moment, that motor could be viewed only as a scientific toy. However, his idea that a rotating magnetic field may be created by switches was not only correct, but was practically achieved after one century. Today, we get, by the use of semi-conductors polyphase alternate currents for the drive of motors whose velocity must be changeable. It could even be said that the Bailey's system is being used presently in modern railway engines.

Independently from Tesla, and, probably, at the same time, Ferraris invented and made a laboratory model of two-phase induction motor. He obtained the magnetic field by passing two phase-shifted alternate currents through two coils physically shifted for 90 degrees. The rotor consisted of a cylinder made of copper. Although knowing very well the electromagnetic theory, he made two mistakes in the analysis of the function of that motor: he neglected the leakage of the flux in the rotor, and he observed, nobody knows why, the efficiency at maximum power of the motor. Because of the first mistake he could not

understand why the motor does not have the highest torque at start, and because of the second mistake he came to the wrong conclusion that that motor can not have the efficiency higher than 0.5. That conclusion provoked the famous Ferraris's statement, often mentioned when people talk about the need of caution when coming to theoretical conclusions without practical check, that a motor made in such a way, that means the induction motor created by polyphase alternate currents, can not be of use in industry to transform electric energy into mechanical work! What a mistake of a talented inventor and respected professor!

We will not describe the research of Marcel Deprez, of Bradly and of others who also described the devices in which the rotation of the rotor was achieved by polyphase currents. All those attempts only illustrate the fact that the time was ripe for the most important invention of Nikola Tesla.

Tesla explained very clearly, in his patents applied for in the fall of 1887, and admitted and published on May 1st, 1888, the invention of polyphase induction motor and he was the first, today there is no doubt about it, to obtain all patent rights for that invention. Tesla, as a difference from his contemporaries, was the first to prove experimentally that induction motors with high degree of efficiency can be made. Tesla understood in a visionary way the importance of his invention for the development of civilization and announced that, without hesitation, to the world. As it is well known, he not only invented the motor, but predicted unmistakably the importance of that motor in the system of production, transmission, distribution and use of electric power, the polyphase system of alterating currents, which made possible the modern life on our planet during already more than 100 years.

5 Investing

People who have money and who are capable of earning money play a very important role in the creation of goods, although they are often underestimated by the scientists. They adopt important decisions about the investments of money in research and, in the case of positive results of the work of researchers, they organize the production. Without their support, many inventors remained unknown.

When they learned about the inventions of Nikola Tesla, many businessmen in the New World offered to him money and help in patenting, with the condition that he transfers to them a part of his possible earnings. It is known that the first Tesla's patents, which he signed as the only inventor, were registered with the right of share on the name of Mr. Peck. It is also well known that Nikola Tesla concluded a very advantageous agreement with George Westinghouse, for conceding the right of use of his patents. Without those people, and many other similar people, Tesla would not start the era of broad

application of polyphase alternate currents, suitable not only for distant transmission of power, but for electric drive as well. The investors helped Tesla to protect in time his inventions, to make the first motors, helped his name to become one of the most famous in the world.

6 Construction

Another very important step was necessary from Tesla's invention of the motor until the motor which started moving the world industry: the design and construction of motors. It is obvious that the construction of the induction motor was not and could not have been the achievement of one man only. The construction and theory of every device, including the induction motor, is the achievement of a great number of talented, educated and experienced people. In the creation, the role of the inventor is obviously the most important one, but it would be quite wrong to think that the inventor should, and must be capable of constructing his invention by himself, and to present the theoretical explanation of the function of the invention.

There exist many data which show that Tesla wanted, at the beginning to make a synchronous reluctant motor. That is shown also in his patent application No. 252.132 of October 12th, 1887. Tesla constructed the induction motor which functioned efficiently in October or November 1887. That is confirmed by Tesla's words written in the patent application No. 256.562 submitted on November 30th, 1887 in which, he wrote: "I discovered that better results in that system may be obtained if the rotation of the poles is primarily used for the induction of currents in closed conductors which are under the influence of the field of the motor, so that the rotation is the consequence of the reaction of those currents and the field".

The Westinghouse Company bought the rights of use of the patents, and engaged Tesla to work on the construction. Tesla left, after one year, the Westinghouse factory and continued by himself the research in other fields of electrical engineering, and then in mechanical engineering as well. In their pioneer constructors' work, Westinghouse engineers did not find the best way. They made motors with salient poles and with frequency of the existing 133 Hz grid, unsuitable fot the induction motor. They succeeded in making single phase motors of small power and to sell them successfully to consumers which had used already for years Westinghouse's grid of alternate current for electric lighting. They spent, without success, a lot of time and efforts in the construction of induction motor for the drive of streetcars, with important negative economic consequences. The reason for that failure is understandable: it was impossible, and it is still impossible, to achieve economical function of an induction motor which is supplied with current of constant frequency, and should function with variable speeds. According to its nature, induction motors function economically

only when they turn at a speed a little smaller than the speed of the rotation of the magnetic field, which is constant if the frequency is constant. At present, the streetcars are still driven by direct current motors, while railway engines are driven, since several years only, by induction motors supplied not with constant, but with variable frequency coming from semi-conductor power converters. So, they started along wrong ways in America: the first one was when they made motors with salient poles, and the second one when they tried to make a traction induction motor for the existing single phase Westinghouse grid with 133 Hz.

In the meantime, in Europe, a group of excellent engineers worked on the construction of the Tesla's asynchronous motor, as it is called on this continent. They not only constructed very good motors, but succeeding in excellent selling and application of those motors, made them the moving force of the industry. Out of those engineers we should obviously mention Brown from the Oerlikon Company in Switzerland and Dolivo-Dobrowolsky from the AEG Company in Germany. They are responsible for the very successful construction of motors without salient poles at the stator and rotor, for putting windings into slots and for the construction of squirrel cage rotor, for the shift from the two-phase to the three-phase Tesla's polyphase system. They should be complimented for the fact that for one time they made induction motors better than those which were made in America, and for the fact that they pointed out, in the best possible way, the obvious advantages of Tesla's motors for the drives with more or less constant speed.

7 Tesla: Researcher, Inventor or Constructor?

George Westinghouse, who made it possible to Tesla to materialize many of his ideas, said once, with deep respect and friendly feelings, but with a mild reproach, from the business point of view: "Tesla considered himself as not being an engineer, a constructor of new machines, just a researcher of new phenomena".

Undoubtedly, Tesla, regardless of what he spoke and of what he wished, was a scientist-researcher, and inventor, and a constructor. Soon after his arrival in America, he became famous as an excellent engineer and successful inventor of useful practical devices. He had a modest income, and could spend a part of that income to experimental verifications of his inventions. He indefatigably thought about polyphase alternate currents and motors. He succeeded in finding sponsors who helped him apply for his most important patents. After the fame he acquired, and with the money he got from Westinghouse for ceding his patent rights, he did not work intensely on the construction of the polyphase induction motor.

He devoted himself to new research. He wanted to achieve wireless transmission of energy to big distances and to make a high tower from which energy would be sent to the most distant places on our planet. He invested in that research his famous perseverance and his talent, and also enormous amounts of his money and of money of other people (several hundreds of thousands of dollars of that time). Although he did not attain the desired objective, during his indefatigable experimental research he discovered many other phenomena important for science. Let us mention just several such discoveries: the phenomenon of resonance of two inductively coupled helixes by the spread intercoil capacity, the harmlessness of his high frequency currents to human body, the properties of high frequency electromagnetic waves, the phosphorescence of rarified gases in tubes under the influence of the high voltage obtained by his transformer, etc. Therefore, Tesla was a very successful researcher, he discovered important phenomena, but, like all researchers, he had to face the full bitterness of failure: he did not discover a natural phenomenon which would allow his imagined wireless transmission of energy.

Bearing in mind his, for that time, admirable successes in the construction of apparatuses which he used in his research, Tesla had to be an exceptionally good constructor, as well.

The knowledge and skill necessary for the construction of the high frequency generator of voltage, which produced the unforgettable and extremely popular lightnings, strongly confirm that opinion. Even today, one needs a lot of skill to make a capacitor for high voltage, to achieve insulation between the windings, to make devices for synchronous abrupt cutting of current. A lot of constructive talent was necessary to make detectors of electromagnetic waves and innumerable other devices, including, as it is well known, many mechanical devices.

Therefore, Tesla was a scientist-researcher, an inventor and a constructor. Respecting the results of his intellectual and experimental work according to their contribution to mankind, it should, however, be underlined that his most important works belong to the class of inventions, primarily in the field of electric power industry. Tesla found out how a rotating magnetic field may be obtained by polyphase alternate currents. Tesla found out how current can be established in the rotor without brushes and collector by electromagnetic induction. Tesla invented the system for the production, transmission, distribution and use of electric power.

In his statements, Tesla always attracted American journalists, and became a legendary person. Since the unit of magnetic induction is called after his name, Tesla is presently the most famous Serbian name in science, and it will be such for centuries. Therefore, both scientists and laymen should talk with great respect not only about Tesla's most important achievements, but about the entire

work of Tesla, regardless of the fact that it is presently determined what Tesla's ideas were attainable and what were not, what are in accordance with scientific truth and what are not. In evaluating Tesla's scientific work, one must take into account the time in which he lived and underline the fact that by the end of the nineteenth century it was pertinent to study the nature and to verify the ideas in the way Tesla did.

Tesla, like every researcher, had sometimes to chose, like a traveler at a crossroads in an unknown region, the way to take. And, naturally, it happened sometimes, as it happened to other great researchers, that he did not choose the best one. Let us imagine what would happen had he, instead of looking for the ways of wireless transmission of energy, directed his talent and his enormous working energy to the research, so near to him, of the apparatuses for the transmission of signals by electromagnetic waves. Maybe he would be presently admitted and glorified as the inventor of radio.

When talking about the construction of induction motors, we can not, at present, understand what made Tesla write, in his famous lecture in 1888, the following: "It seems that the torque is biggest when neither the stator nor the rotor have salient poles; however, as in that case the concentration of field can not be big, probably the best solution is to leave the salient poles on one part of the motor only." Today, we know and we understand why the lack of use of the slots and of sinusoidal distribution of the magnetomotive force slowed substantially the commercial success of Tesla's motor in America. The physical process of the creation of the mechanical torque in induction motor is quite complex. It is not the result of the action of electromagnetic forces on the conductors with current, as it is explained in most of the textbooks, but of the action of Maxwellian pressure on the walls of the slots.

8 Conclusion

Although being very simple from the construction point of view, Tesla's induction (asynchronous) motor is a very complex device, regarding the description of the phenomena which take place in it. Many people took part in the discovery of the natural phenomena which happen in induction motors and in their construction, but Tesla's contribution was of key importance. Tesla was the first to describe his invention mentioning data about the motor which functioned efficiently, which had both the rotor and the stator of iron, with polyphase windings at the stator and at the rotor. His primacy regarding the patent applications is doubtless. He got the greatest possible acknowledgement for his achievement: that magnetic induction is measured by units bearing his name.

Tesla's idea of the application of polyphase currents for the production, transmission, distribution and use of electric energy, the system which he

invented and patented, is obviously, as the contribution to the modern civilization, one of the most important engineering achievements. When he became famous, Tesla sometimes dared to talk about many innovations which he or other inventors would discover in the future. He was right in many of his predictions, as, for instance when he talked about teleautomatics, or about fluorescent lighting, but many of his ideas were unrealistic. In that way the enormous money he earned, of the order of magnitude of hundreds of thousands dollars of that time, he spent on the unsuccessful project of wireless transmission of energy. Also, his great efforts to produce turbines and pumps without blades, were commercially unsuccessful. Tesla's listening of the universe, in the hope that he would catch messages from Mars or from some other planet did not, as we know, bring positive results. But, should those attempts be blamed? In his old days, Tesla distanced himself from pragmatic engineering constructions and indulged in philosophical debates. In financial misery, in which he would end his life had it not been for the material assistance he got from his fatherland, he presented ideas which were harmful for his reputation, like for instance the death rays he believed he invented, which would protect the weak and prevent the arrogant big armies from starting wars.