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The Mini Drive Prototype – a Low-Cost Single Phase Adjustable Speed Drive System on the Basis of Tesla's Motor

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Abstract — **As one of the greatest erudite in the age of electricity, Nikola Tesla presented polyphase system of electrical energy generation and distribution more than one hundred years ago. Today, more than 60% of electrical energy consumption is linked with electrical drives encounting torque actuators that rotate on the basis of Tesla's rotating field. Electric drives with electronic speed control are advantagesly used in home and industrial appliances and automotive field in order to address ever increasing demand for more efficient energy conversion systems that are environmentally friendly. One of such is the MiniDrive prototype, the innovative solution developed at the Laboratory for Digital Control of Electrical Drives at the Faculty of Electrical Engineering in Belgrade, Serbia. MiniDrive is a low-cost single-phase adjustable speed drive with 500W rated power and 1500rpm rated speed, which enables continuous speed control in 150-5000 rpm range with efficiency higher than 70%. The prototype includes Tesla's motor; power factor control implemented power converter and galvanic insulated auxiliary power supply; sensorless control algorithm performed on a low cost RISC microcontroller; digital display for speed and error code information and IrDA communication with a PocketPC. The MiniDrive prototype won the first prize at the worldwide IEEE competition – International Future Energy Challenge 2005 in Chicago, USA.**

Keywords – **Tesla's Motor, polyphase system, Tesla's rotating field**

I. INTRODUCTION

LIVING in the age of electricity, Nikola Tesla gave great contribution together with few pioneers of the time. The ideas and patents that Tesla left during his life indeed enable effective use of energy capacity of the nature in order to make our living easier and better. He lived his live proving that inventors' "ultimate purpose is the complete mastery of mind over the material world, the harnessing of the forces of nature to human needs".One of his first well recognized and adopted inventions is certainly the polyphase system that he proposed for using in electrical energy generation and distribution. This invention is based on his perception that polyphase alternating currents induced in spatially distributed coils on the machine stator produce the rotating field. Today, more than 60% of electrical energy produced in industrial countries is used in electrical drives with motors that rotate on the basis of Tesla's rotating field. Electric drives with electronic speed control are advantagesly used in various home and industrial applications, appliances and automotive field [1]. New inventions are faced with analogous objective as before: to design more efficient energy conversion systems that are environmentally friendly.

International Future Energy Challenge (IFEC) [2] is student competition for innovation, conservation, and effective use of electrical energy. This biannual competition is organized and sponsored by The Institute of Electrical and Electronics Engineers (IEEE) [3]. One of the IFEC 2005 topics was to design high-efficiency motor drive system with rated power of 500W suitable for home appliances. The winning prototype was developed in the Laboratory for Digital Control of Electrical Drives at the Faculty of Electrical Engineering in Belgrade, Serbia. The challenging mission that more than 20 students of graduate and postgraduate studies successfully fulfilled was to implement modern trends in power electronics and process automation on the basis of Tesla's rotating magnetic field.

II. THE POLYPHASE SYSTEM OF ALTERNATE CURRENT

The story of the polyphase system started when young Tesla was at his second year of studies at the classes of experimental physics [4]. Observing the operation of Gramme dynamo machine, Tesla stated that the motor could be started without the use of brushes which was strongly argued by his professor at the time. As a result of great determination Tesla proposed the principle of rotating magnetic field in the early 1882. Only one year later he successfully proved his theory constructing the first two-phase induction motor with a disc rotor. Soon after, Tesla filed several patents, well known as

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patents of Tesla's polyphase system, describing the invention of the electromagnetic motor, the transmission of energy by means of a polyphase system of alternating current, and the system of electrical distribution for power plants. However, the possibility of applying them was poor as the direct current power system dominated the process of electrification at the time. Great impact which attracted the attention of the professional public was a lecture that Tesla gave in front of the American Institute of Electrical Engineers on "A New System of Alternate Currents Motors and Transformers" in 1888. This event helped him to get Mr. George Westinghouse as a strong partner for the upcoming "War of the Currents". As Nikola stated "his new partner was the only man in the world who, in the given circumstances, could take on his alternating current system and win the raging battle against prejudice and the power of money". Westinghouse comprehended the possibilities that Tesla's invention offered and focused on the big event that later took place – The Chicago World Fair in 1893. The "War of the Currents" ended when Westinghouse was awarded the bid to light up the town during upcoming event. With the great success at the World Fair, Tesla's alternating power system won once again. The same year a decision was brought concerning the method of exploiting the waterfall of the Niagara River that we are standing in front of. Westinghouse Electric and Manufacturing Company proposed the application of a generating system with three two phase generators, each powered by 5,000 HP. On the other hand, the General Electric Company gave its support to a three phase transmission and distribution system. The first transmission of electric energy was made from the Niagara to the town of Buffalo which was 22 miles away. The age of modern electrification has started. At the time Tesla started his research work in a completely different field of science which was the field of high frequency currents.

Today, motors that rotate on the basis of Tesla's rotating field are widely used in machine tools, industrial robots, automated presses, elevators, conveyers, rolling mills, compressors, pumps, electrical vehicles and cranes. Digitally controlled electric drives have reached mature phase in their development. The increased use of microelectronics in power control circuits enables the implementation of complex control concepts, allowing the production of environmentally acceptable, self optimized motor drives with applications ranging from precision machine tools to traction drives with Tesla's induction motor in high-speed passenger trains. Many elements and modules of the drive system are already consolidated; widely accepted solutions exist for the power converter topology, motor types and basic control structures. These well tested solutions are unlikely to undergo significant changes in the years to come. The research and development efforts are directed towards the remaining drive problems, where substantial contributions are expected in the future. Some of these problems are: i) Present drives radiate relatively high levels of electromagnetic, acoustic and thermal pollution; ii) The drives use a large number of sensors, the wiring and cabling is fairly complex and the cost of the drive package is still excessive for most applications; iii) Elaborate installation and commissioning make the human operator inevitable in the startup, repair, replacement and run-time situations.

Integration of the drive power converter into the motor frame allows for a significant cost reduction and more simple installation and wiring. With an integrated motor converter package, the motor cable exists no more. The cable capacitance, electromagnetic radiation and the reflections of the dV/dt wave are cleared away, reducing greatly the problems of the EMI and an early breakdown of the motor insulation. To make the integration concept applicable in the field, it is indispensable to solve complex thermal management problems of the integrated drive package. At the same time, the semiconductor technology is to provide for the power and signal processing devices that can operate safely at motor case temperatures.

III. International Future Energy Challenge 2005

International Future Energy Challenge (IFEC) is biannual competition organized and sponsored by The Institute of Electrical and Electronics Engineers (IEEE). This student competition promotes innovation, conservation, and effective use of electrical energy. The IFEC objectives are to encourage development of technologies, to incorporate practicality, manufacturability and affordability into competition process, and to improve education through development of innovative team-based solutions to complex problems. The IFEC 2005 target hardware cost were limited by US$40 for a combination of motor, power electronic driver, and controller that can operate from a single-phase residential source; the drive system should deliver rated shaft load of ¾HP (or 500W) at 1500rpm, exhibit a useful speed control range from 150rpm to 5000rpm, and provide power efficiency of at least 70% for loads ranging from 50W to 500W at a specified speed. The prototype should also maintain levels of performance, reliability, and safety according to IEC standards.

The IFEC 2005 gathered more than 30 international student teams that had been developing innovative drive systems for 15 months. The final competition brought only three teams to Chicago, USA. All three final prototypes used electrical motors that rotate on the basis of Tesla's rotational field.

IV. The MiniDrive prototype

The MiniDrive prototype [2], the winner of the International Future Energy Challenge 2005, is shown in Figure 1. This integrated motor – converter system is developed at the Laboratory of Digital Control of Electrical Drives at The Faculty of Electrical Engineering in Belgrade, Serbia. The prototype include Tesla's motor; power converter with power factor control; galvanic insulated auxiliary power supply; sensorless control algorithm performed on a low cost

RISC microcontroller; digital display for speed and error code information; IrDA communication with a PocketPC.

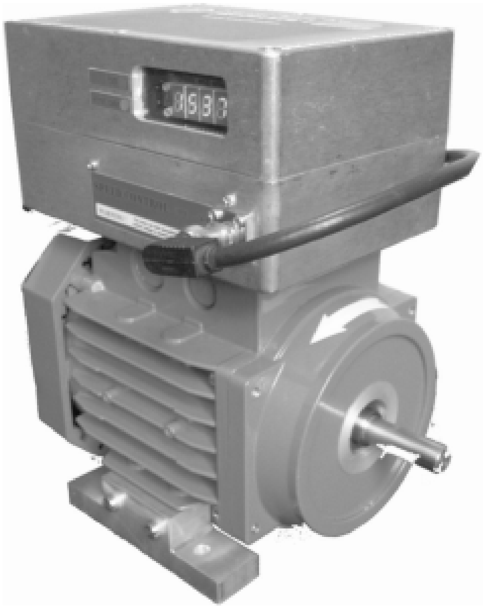

Figure 1: *The MiniDrive prototype*

The whole project that included planning, developing and promoting MiniDrive prototype was undertaken by the team consisted of 19 students of graduate and undergraduate studies and one professor. The professor Slobodan Vukosavić, as the team mentor, supervised the project as whole, according to the IFEC rules. Students of undergraduate studies were in charge of engineering and marketing work, while two graduate students lead the project and managed all its tasks. The MiniDrive team included four teams: MD drive, MD hardware, MD software, and MD marketing. Each group had one student leader and every task within the group is performed by at least two students.

The tasks handled by MD hardware group included design of auxiliary power supply; power, control and display circuits. One of the most critical issues was to design space limited printed circuit board (PCB) which is placed inside the motor frame. The power circuit consists of full-wave rectifier, DC link storage capacitor with current sensor resistor and three-phase inverter. In order to reduce the harmonics according to IEC Standard EN61000-3-2, the power circuit also includes power factor correction (PFC) and EMI filter. The use of PFC is multi beneficial since it shapes the input current to maximize real power available from the mains; it equalizes the phases of input current and voltage which significantly reduces higher input current harmonics and, therefore, power distribution losses. Furthermore, PFC circuit saves the PCB space since the system requires only one bulk capacitor and there is no need for 110/220V switch, which makes the drive not prone to operator error.

Flyback converter enables galvanic isolation between system auxiliary power supply and the power mains. The anticipated converter input voltage is in the range of 250Vdc to 400Vdc, while the output power is 6,5W. The converter provides three voltage outputs and its design enables stable work at the ambient temperatures up to 85°C. The control circuit includes RISC general purpose microcontroller used for information processing; microcontrollers used for data acquisition and display; analog input circuit; hardware triggered over current protection.

The printed circuit board is shown in Figure 2. It is placed in originally designed aluminum case for PCB housing. The case is also used as a heat sink for temperature critical components and to hold LED display and IrDA port.

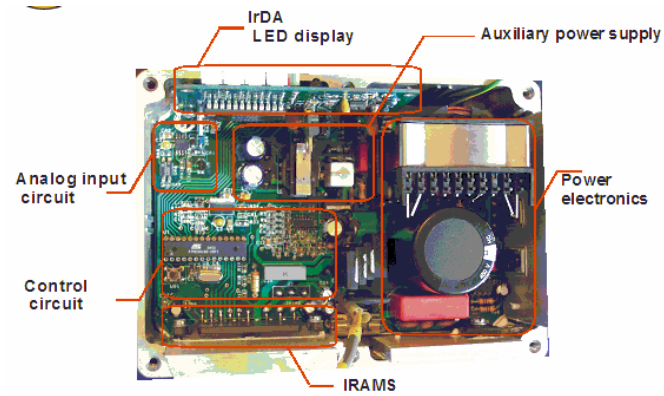

Figure 2: *Hardware aspect of the MiniDrive prototype*

The tasks undertaken by the members of MD software handle control algorithm, A/D conversion, PWM signals generation, protections and data exchange. Embedded code execution includes main program and interrupt routines layer programmed in both C language and assembler. Considering strict limitations regarding the overall system cost, the speed control algorithm should require neither excessive numerical calculations nor expensive speed sensors. Therefore, the only feedback signal DC link current which is proportional to motor load. The speed control uses sensorless quasivector speed regulation with slip estimation based on DC link current. Space Vector Pulse Width Modulation (SVPWM) algorithm powers the inverter transistors. This algorithm provides better utilizing of DC bus voltage and lower switching losses. The software implemented protections include temperature and DC link over and under voltage protections. Overall RISC resources consumption is shown in Figure 3.

OPERATION	CYCLES	TAKEN
SVPWM algorithm	284	7%
AD conversions	98	3%
Protections	467	12%
Control algorithm	2275	56%
UART communication	376	10%
LED display	676	17%

Figure 3: *RISC resources consumption*

The Minidrive prototype met all the technical requirements set by the IFEC 2005. Unfortunately, due to limited space of this paper, only two test results are presented. Figure 4 shows system response on the speed reference set to 1500rpm when the motor loads are 50W, 150W, 250W, 350W and 500W.

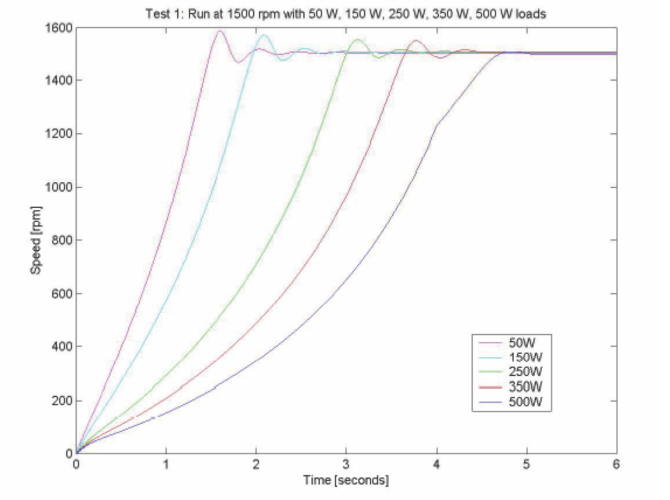

Figure 4: *Prototype tested on various loads*

Figure 5 shows the low speed range test in which load is set to 3.18Nm while speed reference is step changed.

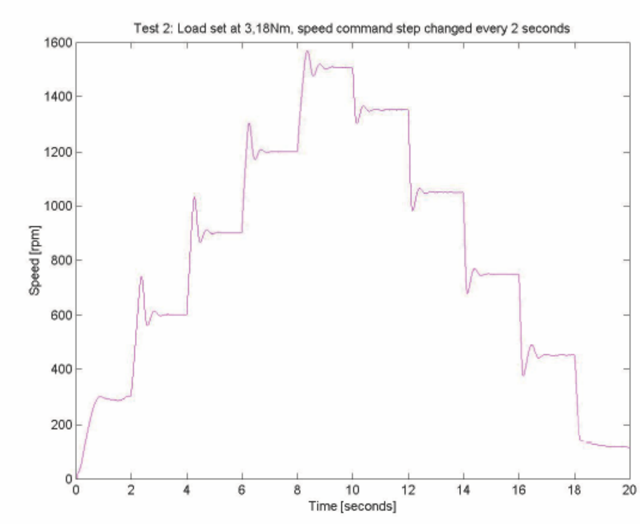

Figure 5: *Low speed range test*

The members of MD marketing team were in charge of project promotion, fund raising and communication with project partners. The promotional activities of project and its objectives took place in various paper, electronic and TV media; in faculties and high schools; at international conferences. One of the articles is shown in figure 6. The project partners include representatives of many national ministries, local government, foreign and national companies.

Belgrade University, Serbia & Montenegro:

Belgrade reaches final stage in the Future Energy Challenge

University of Belgrade Student Branch Mini Drive Team.

EVERY OTHER year, four IEEE societies (Power Electronics, Industry Applications, Power Engineering and Industrial Electronics) run a worldwide Future Energy Challenge drive with characteristics that comply with strict standards. The most important criteria is the production price that should be under US$40. The competition allows

Figure 6: *An article published in IEEE Region 8 Magazine*

The educational impact of this project is beneficial great. Each team member gained great engineering practice. Working in team environment provided new experiences in decision making processes, sharing responsibilities and communication among team members. The students involved in the project published several scientific papers, many progress reports, technical documentation and user manual. On the other hand, the education is also provided to those who were not involved in the project directly. Many of the project results are easy to use for the education of younger students.

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