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The Use of Wireless Networks and Mobile Applications in the Control of Electric Machines

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Abstract: The paper presents the implementation possibilities of remote control by use of wireless communication and mobile application dedicated to controlling systems of power electronics converters. The article focuses on Bluetooth and Wi-Fi technologies as they are currently the most commonly used in modern mobile devices. The authors wanted to check the usefulness of those methods in the application of a classic drive set with a DC motor. The MIT App Inventor programming environment, which allows quick prototyping of the mobile graphical interface, was used to develop the mobile application. The developed prototype of the mobile application is the second thread of the article, the aim of which is to propose a mobile application interface that enables safe control of the electric drive in an open loop. By repeated testing of the graphical structure of the application and the controls used, the authors obtained the final form of the interface, which, in their opinion, is absolutely required when developing such programs. The evaluated control strategy has been also used to control the rotational speed of a permanent magnet DC motor supplied by a three-phase thyristor rectifier. This paper's research results have shown the proposed solutions' advantages and disadvantages.

Keywords: wireless control; thyristor rectifier; IoT; Arduino; NodeMCU; Bluetooth; Wi-Fi; electric machine; MIT App Inventor; remote control; mobile application

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1. Introduction

Nowadays, the Internet has covered almost all disciplines of modern life [1–4] and wirelessly controlled devices have become more and more popular. Currently, almost every person is equipped with a mobile device that can act as a user interface for controlling other objects [5–7]. Wireless communication, which is now inextricably linked with mobile devices, is relatively cheap and readily available. We live in the era of the Internet of Things (IoT), a global intelligent network which has developed expeditiously over the last twenty years simultaneously with advances occurrence in networking technologies, including Bluetooth, Wi-Fi, and long-term evolution (LTE) [8]. The IoT is the strategy of extending Internet connectivity beyond standard electronic devices, such as laptops and smartphones, to any type of household appliances, for instance, fridges, washing machines, ovens [3,9] and creates an opportunity to manage processes from the level of a mobile application. Smart applications could serve people and provide them with support in intelligence systems such as transportation, healthcare, smart agriculture, smart houses, smart cities and smart grids [10]. A smart grid is characterized by the capability of two-way communication of both electricity and data [11]. This is based on communication technologies and advanced metering infrastructure which enables monitoring, controlling and reacting to unexpected and unpredictable changes in the power system. Recently, the number of processes and devices which are monitored and controlled remotely has been increasing. One of the possibilities to control a device in such a way is the use of a mobile device that provides a specific type of wireless communication like Wi-Fi or Bluetooth, and a graphical interface in the form of a mobile application. It is observed that mobile application development for smartphones has evolved vastly due to ubiquity and popularity among end users who are using them more than ever. This fact has resulted, however, in developers' focus on the improvement of users' experience to the detriment of security [5,12].

Since the remote control of household devices is no longer a problem, the applicability of mobile devices with wireless transmission to control industrial automation devices, such as electric drives, seems to be also achievable. However, this is more demanding due to the need for ensuring greater requirements for the safety and reliability of the control process. Remote control, in particular one that uses wireless technology to transmit signals, allows maintaining a safe distance from a device under operation. In addition, the use of microcontrollers enables the collecting and sending data from sensors of various types, for instance, temperature or humidity, in a dispersed manner. What is more, remote control reduces costs and improves control efficiency by reducing the number of wires and eliminating the problem of their arrangement. Nevertheless, wireless transmissions are not devoided of disadvantages. In particular, they are exposed to the influence of external factors, which are mainly other radio systems or electromagnetic disturbances of various origins, or disturbances from converter systems in case of industrial conditions.

Among the various categories of mobile applications, such as online games and social networks, there are also critical ones that could guarantee a high level of reliability and quality [13,14]. From this point of view, a mobile application can be considered as one of the most relevant elements of the entire control system, as the application's interface is what the user has direct contact with. The properties of the application also determine the attending of a system to some extent. The safety of the operator and the device under control from the level of such an application often depends on whether it is written in accordance with the accepted standards and on its ergonomics. Applications that control the operation of electric motors or other industrial devices have particularly higher functional and safety requirements than ones that are typical programs that anyone can install on their smartphone by downloading them from applications stores (e.g., Google Play Store, the Apple App Store). On the other hand, applications of this type are often developed by electronic or electrical engineers who are not always proficient in programming mobile or web applications.

Figure 1 shows the idea of open-loop control of a DC electric drive in a graphical form. The figure also indicates the problems to be solved when designing a wireless electric drive control system. The authors distinguish four basic problems to be rectified in this type of system. The first is the interface of the mobile application, which should be precise and ergonomic. The other two problems arise from the specifics of the chosen wireless transmission technology and are connected to the distance between the mobile device that provides the interface for the system user and the object itself. These properties, for a given transmission technology, mainly depend on the frequency of the transmitted signal and modulation. An equally important and identified problem is that open-loop control requires the creation of a means of verifying connection continuity and information coupling, which may be unnecessary in the case of closed-loop control systems. In an open-loop control system, it is a user who sets control parameters and observes the response of the object, however, it is sometimes impossible in the case of wireless control, in which the distance from the object is significant. Therefore, the facility should provide a mobile device, acting as an operator panel, with feedback information about the status of the device and the connection.

The subject of this paper is the remote control of DC electric drives based on wireless communication and mobile applications. The paper comprises a description of both the most important functionalities that such a mobile application should provide, and the programming environment that can be used for the rapid prototyping of such an application by engineers with basic programming competencies. Particular stages of the conducted research include the implementation of the remote control of two wireless transmissions and the development of a mobile application in the MIT App Inventor environment. The presented remote-control system has been tested on a three-phase thyristor rectifier with a DC machine with permanent magnets (PMDC).

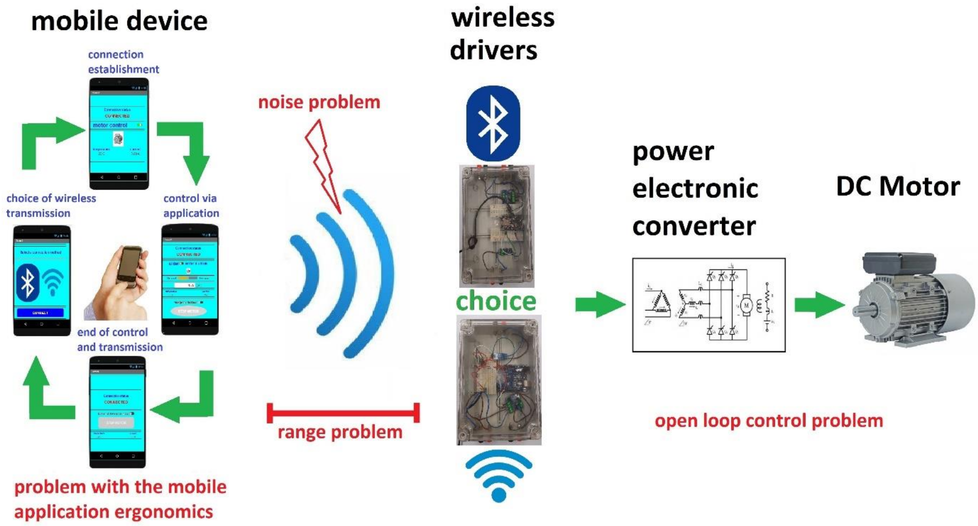


Figure 1. Schematic diagram of an open-loop remote control system of a DC electric drive.

2. Selected Wireless Transmission Technologies

There are two main wireless transmission technologies used in remote control strategies: Wi-Fi and Bluetooth. They are easy and cheap to implement, they have been tested under various conditions and each smartphone is equipped with such a standard. Another advantage is a relatively simple implementation of these technologies on currently accessible digital platforms such as Arduino, Raspberry PI and NodeMCU v3. In addition, their range and data rates meet the requirements with an excess.

Bluetooth belongs to the open specification of computer and telecommunication technology IEEE 802.15.1, which enables wireless communication over short distances within a range of about 10 m [15,16]. Due to the fact that the Bluetooth communication range is small, it is most often used in order to replace cable connections of ICT (information and communication technology) and computer devices in close vicinity of the computer. Bluetooth wireless communication creates a WPAN (IEE 802.15) Personal Area Network (WPAN), in which devices change their location in accordance with the users' movement. These types of devices include mostly mobile phones, smartphones, digital cameras, audio sets, cameras, printers, scanners, and other devices in which wired communication is of little use [16–18].

Wi-Fi network constitutes the most popular wireless communication technology used by devices nowadays and belongs to the 802.11x standard, which describes WLAN local networks. It uses radio waves for communication and data transfer. Using a Wi-Fi module is notably suitable for bandwidth, high speed and large distance coverage as well [19,20]. The frequency bands used by Wi-Fi network are 2.4 GHz and 5 GHz, however, there are several varieties of this technology as it has been evolving since 1997. The typical ranges of Wi-Fi transmission in an open area and inside buildings are about 100 m and 30–50 m, respectively [21,22]. The list of selected standards of 802.11 transmission is presented in Table 1.

Table 1. List of selected standards of the 802.11 transmission.

Standard	Theoretical Throughput	Frequency	Date of Introduction	Modulation Technique
802.11n	600 Mb/s	2.4 GHz and 5 GHz	02-2006	OFDM
802.11ac	1 Gb/s	2.4 GHz and 5 GHz	2013	OFDM
802.11ax	10 Gb/s	2.4 GHz and 5 GHz	2017	OFDM

Presented list summarizes selected parameters and features of both described wireless transmissions. Paper [10] presents a broad comparison of protocols used in Internet of

Things (IoT) technologies, for example, LoRaWAN, NB-IoT, ZigBee, 6LoWPAN, etc. In typical IoT applications, wireless transmission technologies characterized by very low energy consumption are the ones which are most often used (e.g., devices supporting them can operate on a battery for a year or two). However, these are mostly low-speed solutions and they require specialized and dedicated devices to build the transmission infrastructure. A comparison of selected parameters of the applied wireless transmission technologies with the technologies used in IoT solutions is presented in Table 2 [23].

Table 2. Summary of selected parameters and features of the Wi-Fi and Bluetooth transmissions.

	Typical for Mobile Devices		Typical for IoT	
Feature	**Bluetooth**	**Wi-Fi**	**LoRaWAN**	**ZigBee**
Bandwidth	Low	High	Very Low	Very Low
Hardware equipment	Bluetooth adapter only	Wi-Fi access point and Wi-Fi adapters required	Dedicated devices	ZigBee Coordinator, ZigBee Route, ZigBee End Device
Topology	Point-to-point	Point-to-point, broadcast, and mesh networking	Star-of-stars	Star, Tree, Mesh
Range	10 m	30–50 m in buildings, 100 m in open field	10–15 km	10–100 m
Security	Less secure	More secure	More secure	More secure
Power consumption	Small power consumption	Much more power consumption	Very small power consumption	Very small power consumption
Frequency	2.4 GHz	2.4 GHz and/or 5 GHz	169 MHz, 433 MHz, 868 MHz (Erupe) 915 MHz (North America)	2.4 GHz 868 MHz and 915 MHz (selected regions of the world)
Speed	Slow—about 1 Mbps	Fast—about 1 Gbps	Slow—about 50 kbps	Slow—about 40–250 kbps
Flexibility	Limited number of users	Large number of users	Very large number of users	Limited number of users
Modulation	GFSK	OFSM or QAM	Chirp Spread Spectrum	BPSK or O-QPSK
Ease of use	Very popular and widely available Simply and easy to use	Very popular and widely available Complex software and hardware as well as configuration required	Simply and easy Difficult access to technology—it is developed by about 500 companies in the world to use	Simply and easy to use Difficult access to technology—it is developed by about 150 companies in the world

Figures 2 and 3 show the diagrams of systems that constitute controllers realizing described methods of wireless transmissions. They also give the possibility of the measurements of consumed current and the value of temperature on the machine housing, which is an important function due to the safety aspect since the presented system operates in the open loop control. These measurements, except their major function which is the monitoring of machine operation status, constitute checking signals. They confirm the correct operation of wireless communication. In case of a lack of it, the controller switches to the automatic engine shutdown mode. In the diagram in Figure 2, there is an Arduino UNO that participates in receiving and transmitting information from the smartphone to the machine and vice versa. The Bluetooth module HC-05 is responsible for the wireless transfer of information. The temperature sensor is a block described as DS18B20, and the current measurement is performed by the ACS712-20 A system. LCT-167 PWM is a device that amplifies the PWM voltage from 0–5 V to 0–10 V whilst an external voltage supply of 12 V has been connected to the LCT-167 PWM device.

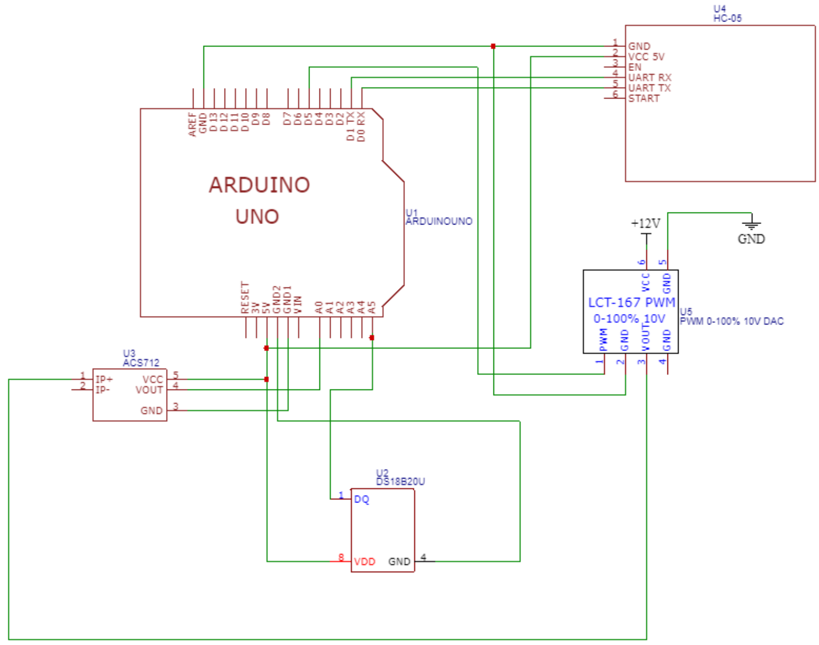


Figure 2. Schematic diagram of the control system using a Bluetooth transmission module.

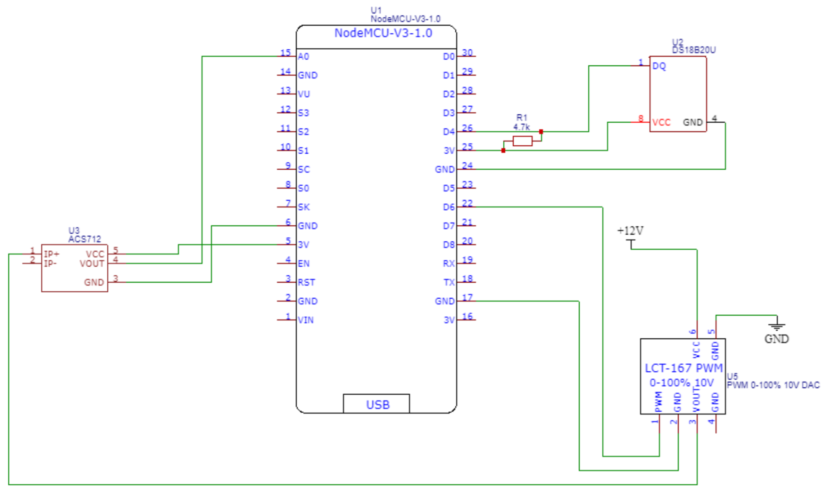


Figure 3. Schematic diagram of the control system using a Wi-Fi transmission module.

Figure 3 depicts a control system using Wi-Fi communication module. The main element of the system is the NodeMCU-V3-1.0 microcontroller which is equipped with 10 digital outputs/inputs and 1 analogue and can be powered from an external power source or via USB. The ESP8266 module embedded in the microcontroller is responsible for wireless communication. Smartphone connects to it directly after starting the operation of Wi-Fi server or through a router. Temperature and current are measured with the same electronic circuits that are responsible for the measurements in the control system via Bluetooth (temperature-DS18B20, current-ACS712-20 [A]). The DS18B20 thermometer is connected to the digital output marked in the diagram as D4 while the ACS712 sensor is connected to the A0 analogue input. In the case of PWM voltage control, the LCT-167 PWM module is used again, and its output is connected to the D6 PIN of the microcontroller. Similarly to the previous case, the laboratory system is connected to the IP (2) (ACS712) and GND (4) (LCT-167) inputs.

3. Programming Environment for Prototyping a Mobile Application

There are various technologies that enable the creation of mobile applications of high complexity operating on different operating systems and hardware platforms. Among them, the most popular are tablets and smartphones which are supported by Android or iOS systems. The article presents an application written in an environment designed for Android since it is a free and open-source operating system based on Linux [24,25]. Authors have chosen MIT App Inventor because this platform gives engineers great opportunities to provide their projects' users with a modern interface. Simultaneously, this program offers a graphical interface that supports the work of an engineer ensuring an easy way of designing and programming applications as it uses Scratch programming language. The environment itself has many built-in functions that facilitate, for example, the handling of broadcasts or the visualization of content.

The implementation of remote control of the power electronics converter requires the development of at least two types of programs. The former has to support a digital platform that is installed at the converter and directly transmits control signals to the power converter. In this case, the transmission based on Bluetooth and Wi-Fi is between a phase controller of a thyristor rectifier and software on a mobile device. The latter, however, is demanded by a mobile device. This one constitutes an application that is a graphical interface designed for a system user.

In both versions of used drivers, the software for digital platforms has been written in the Arduino IDE environment as both Arduino UNO and NodeMCU v3 are compatible with it and have appropriate libraries. The programming of the above-mentioned digital platforms is not the subject of the article, therefore, only basic information has been provided [25].

In this paper, authors bring the focus on the design and implementation of a mobile application developed for a DC electric machine supplied by a three-phase thyristor rectifier. Figure 4 shows the interface of this application, which consists of five views. It has been designed in MIT App Inventor and supports wireless transmission in Bluetooth and Wi-Fi technologies. The presented application is built on one screen, but depending on selected buttons, some of the widgets expire, and then the elements constituting another view appear. Such an approach is safer than scroll screens because all of the available options are within reach of a user, which is especially crucial in case of failure when access to a quick emergency shutdown of a motor is demanded [26,27].

The application's graphic is designed to provide safe, reliable and smooth control, which requires readily available options and quick response. Such an interface, unlike ones of the applications of general use, should not be extensive. Changing the motor rotational speed must be smooth, but at the same time take into consideration physical limitations, such as the inertia of the machine. Therefore, shifting the position of the slider, which results in speed change, occurs with a certain delay. In addition, there is a function to safely shut down the motor, which in most cases must take place with a certain delay in order not to lead to a sudden stop of the device that supplies the machine [26,27].

Figure 4. The interface of the developed mobile application with sequentially switched screens; from the left: screen 1, establishing a connection (Bluetooth or Wi-Fi); screen 2, enabling control; screen 3, motor rotational speed control (using a slider or entered value) with an emergency stop; screen 4, motor shutdown; screen 5, disconnection.

4. Model of the System and Simulation Tests

The main circuit structure of a system is shown in Figure 5. Simulation tests have been conducted in PLECS software to determine exemplary waveforms and frequency spectra of signals which occur under the proper operation of the system. The simulation constitutes also a tool to verify the correct operation of the laboratory system.

Figure 6 depicts the obtained waveforms whereas their spectra are shown in Figure 7. The results encompass motor current and voltage, as well as the rectifier's input current and voltage.

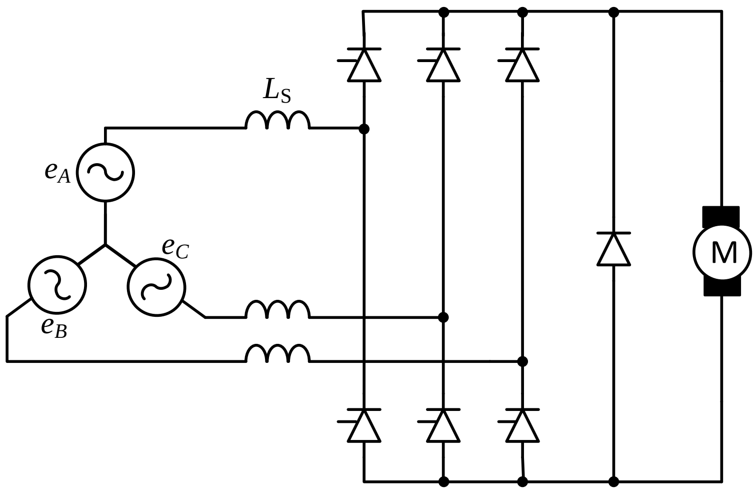


Figure 5. Main circuit structure.

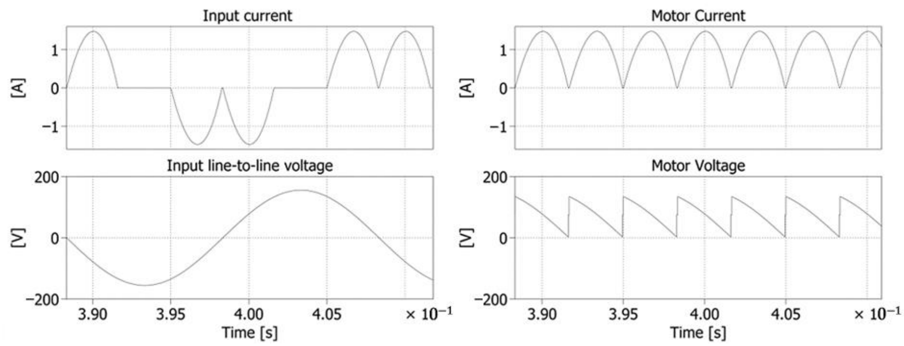


Figure 6. Simulation results for the firing angle of the rectifier's thyristors equal to 60°.

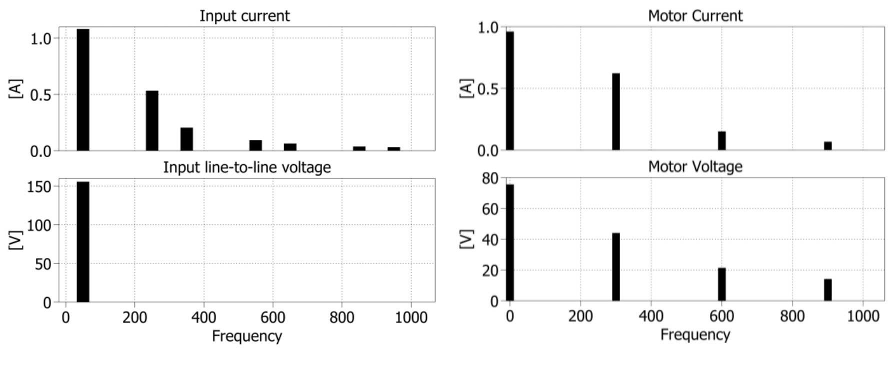


Figure 7. Simulation results for the firing angle of the rectifier's thyristors equal to 60°.

5. The Use of Wireless Transmission and Mobile Application in Control

The developed mobile application in a form of a user interface for controlling the electric motor via a wireless network has been used to modernize the research stand in the power electronics laboratory located at the Gdynia Maritime University. This stand has a set of modules with thyristors controlled from a three-phase phase angle controller, which allows the control of rectifier output manually by using a traditional knob. The range of control voltage is $0 \div 10$ V. It corresponds to the scope of firing angle $0 \div 180°$. The relation between the control voltage and the firing angle is linear. The higher value of the control voltage, the higher value of the firing angle and the lower the rotational speed of the DC motor. The control is performed in an open-loop and does not include the feedback from the value of the motor rotational speed. The methods described earlier in the text enable PMDC machine rotational speed control from the level of mobile application with the use of wireless communication. In this case, a constant numerical value is sent from the application to the microcontroller in order to generate PWM signal. Its average value is passed to the controller which defines the firing angle. Then, based on the value of the firing angle, thyristor switching pulses are generated. The values of the reference voltages and the firing angles of the thyristors are presented in Table 3 and Figure 9. The LCT-167 PWM system is responsible for converting the PWM voltage to its average value (Figures 2 and 3). The designed system is meant to enable the remote control of such a system and permit a comparison of traditional control with a remote one. The view of research stand with both types of control strategies is depicted in Figure 8.

Table 3. Measurements for both control systems with wireless communication.

No.	(Bluetooth) PWM Value [%]	(Wi-Fi) PWM Value [%]	Thyristors Firing Angle [°]	Rotational Speed [RPM]	Motor Supply Voltage [V]
1	54	54	90	100	8
2	48	49	85	533	31
3	38	39	70	1075	70
4	32	34	60	1365	87
5	30	32	55	1490	95
6	26	28	40	1850	115
7	25	27	30	1987	122
8	21	23	15	2100	130
9	19	21	0	2190	135

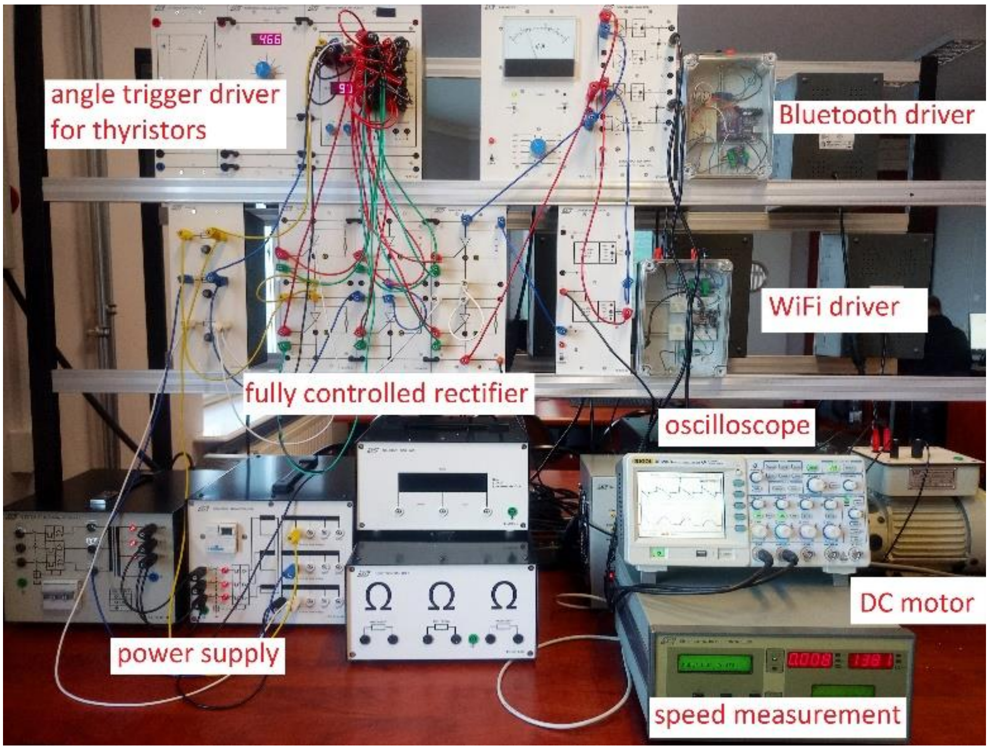


Figure 8. Laboratory stand.

Verification of the proper operation of the application and wireless transmission was performed in the power electronics laboratory. The developed control application was used to control the rotational speed of a PMDC motor supplied by a three-phase thyristor rectifier, whose communication with a mobile device was via a Bluetooth or Wi-Fi module. The rectifier supply line-to-line voltage was 3×110 V, while its frequency was equal to 50 Hz. The test results for control using both the Bluetooth and Wi-Fi technology are shown in Table 3.

Figure 9 shows the characteristics of the dependence of the supply voltage on the motor rotational idling speed and the dependence of the PWM value of both the Bluetooth and Wi-Fi technologies on the thyristors firing angle. A PWM signal between 0% and 100% duty cycle corresponds to Bluetooth and Wi-Fi PWM values between 0–255 and 0–1024, respectively.

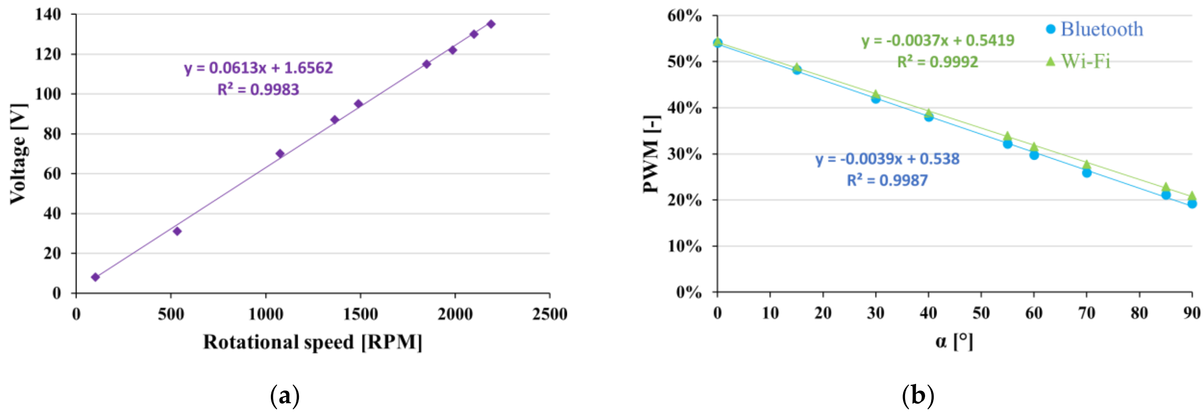


Figure 9. The dependence of the engine supply voltage on the rotational speed.

The presented measurements show that the motor starting was at the thyristor firing angle of 90°, while at firing angle equal to 0° the machine reached a speed of 2190 RPM while its supply voltage was 135 V. This value is close to the theoretical value expressed by the following equation:

$$U_{d\alpha} = \frac{3}{\pi} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \sqrt{2} U_p \sin \omega t d\omega t = \frac{3\sqrt{2}}{\pi} U_p \cos \alpha = 1.35 \cdot U_p \cos \alpha, \quad (1)$$

where:

$U_{d\alpha}$ is the voltage on the DC side of the rectifier, while U_p is the line-to-line supply voltage. The dependence of the motor supply voltage on the rotational speed is linear for almost the entire tested range.

The exemplary voltage and current waveforms obtained for the firing angle of the rectifier's thyristors equal to 60° are shown in Figures 10 and 11, while their frequency spectra are in Figures 12 and 13. Figure 10 presents the waveforms when the motor is at idling speed, while Figure 11 shows when the motor is loaded.

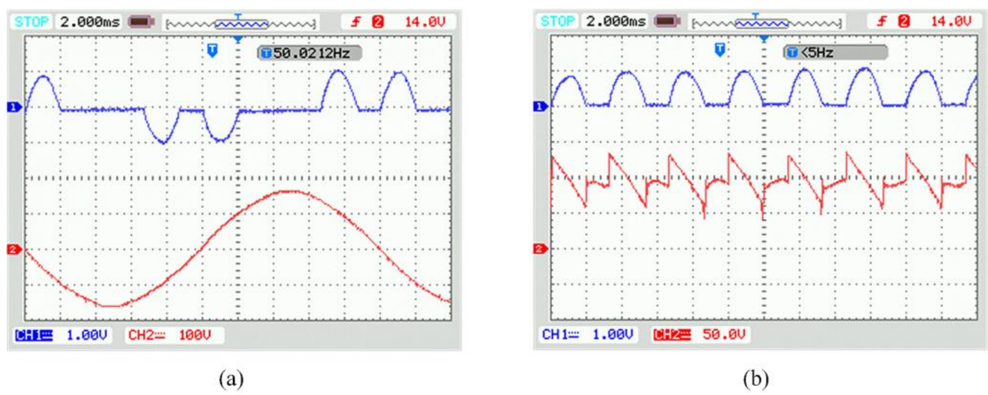
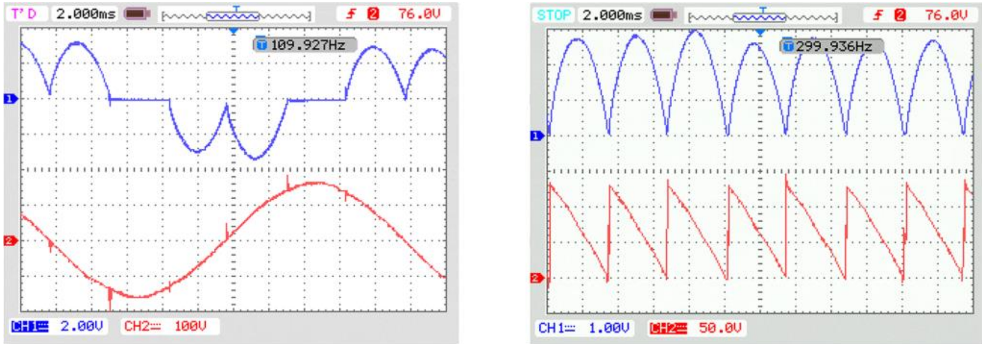
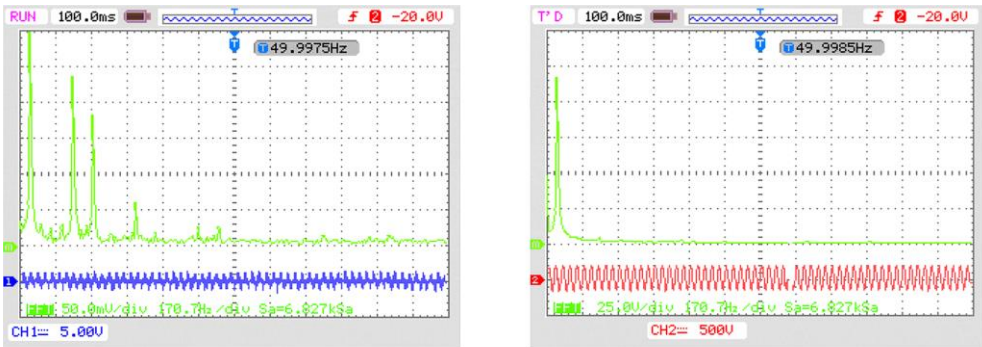


Figure 10. Exemplary results; the firing angle equal to 60°; motor idling speed; (**a**) input current and input line-to-line voltage waveforms; (**b**) motor current and motor supply voltage waveforms.



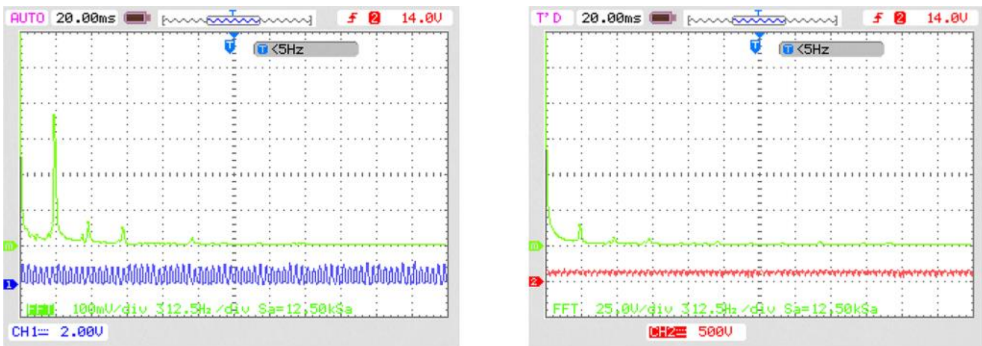
(a) (b)

Figure 11. Exemplary results; the firing angle equal to 60°; motor loaded; (**a**) input current and input line-to-line voltage waveforms; (**b**) motor current and motor supply voltage waveforms.



(a) (b)

Figure 12. Frequency spectra of input current (**a**) and voltage (**b**) waveforms; the firing angle equal to 60°; motor idling speed.



(a) (b)

Figure 13. Frequency spectra of motor current (**a**) and motor voltage (**b**) waveforms; the firing angle equal to 60°; motor idling speed.

The voltage and current waveforms obtained during the laboratory measurements, as well as their frequency spectra, were consistent with the results achieved in the simulation tests. The signal frequency spectra did not show any impact on the wireless transmission systems, as the frequency ranges of the electrical signal were different from the ones used in the wireless transmissions. Therefore, the signals emitted by the converter did not affect the transmission of the control signals produced by the developed wireless controllers. The values of the measured motor currents were 185 mA for the motor at an idling speed and 1 A for the loaded motor. These measurements are in agreement with those displayed on the application screen, for which the values were 182 mA and 1.02 A. Temperatures gained by the motor and obtained through the use of the application are 23 °C when the motor was at an idling speed and 26 °C when it was loaded.

The operation of wireless communication in a remote-control system was tested in dependent of the distance between a mobile device and a PMDC motor drive and its supply. During testing, other machines placed in the laboratory were under operation to obtain conditions similar to those prevailing in the production hall. Bluetooth and Wi-Fi were tested at the following distances from the object: 3, 7, and 11 m. Such values were chosen on account of the practical utilization of such a system, as well as the visibility of the object as it cannot be out of sight. Long-distance control would require the introduction of an object's visual preview, for instance from a camera.

The most significant indicators of the proper operation of the control system are presented in Table 4.

Table 4. List of system performance quality indicators depending on the distance.

<table>
<tr><th>Distance</th><th>3 [m]</th><th>7 [m]</th><th>11 [m]</th></tr>
<tr><td>Object visibility</td><td>Very good</td><td>Good</td><td>Poor</td></tr>
<tr><td>Bluetooth control</td><td rowspan="2">Continuous connection. Smooth control. Control parameters are updated on a regular basis. Full control over the object.</td><td>Intermittent connection. Intermittent control. Control parameters were not updated on a regular basis. Full control over the object was not maintained</td><td>No connection and no control possible. No information about control parameters. There was no control over the object.</td></tr>
<tr><td>Wi-Fi control</td><td colspan="2">Continuous connection. Smooth control. Control parameters are updated on a regular basis. Full control over the object.</td></tr>
</table>

6. Conclusions

The performed tests have shown that it is possible to smoothly control the rotational speed of a PMDC motor supplied by a three-phase thyristor rectifier by remote control system using wireless communication. Both Wi-Fi and Bluetooth methods ensure the same level of control accuracy. The module communicating via Wi-Fi offers the ability to control the system from anywhere and covers longer distances than Bluetooth. The only necessary condition to connect to the controlled object is to have a smartphone with a mobile application and access to the internet. Mobile applications are becoming the basic GUI interface for modern technical systems from various fields of engineering. The proposed shape of the application indicates important aspects of its design and ergonomics. The proposed remote-control system could be suitable for some industrial requirements and locations.

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