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CAN Bus Based Firmware Update System for Distributed Embedded Systems Consisting of ARM Cortex-M0 Series Microcontrollers

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Abstract

In this study, design of a firmware update system for distributed embedded systems consisting of nodes with ARM Cortex M0 microcontrollers is presented. The nodes in the system are connected to each other over high speed CAN Bus 2.0A protocol and the system is controlled by a PC via a graphical user interface. The system allows user to update the Firmware of system nodes through the CAN Bus network. Complete firmware update system for distributed embedded systems with CAN Bus field network is provided by the system designed in this study. With the custom bootloader developed during this study, in application firmware update over CAN Bus feature is integrated to 32 bit STM32F072 microcontroller.

1. Introduction

While designing and developing embedded systems, the firmware is modified several times. As a result of the changes in the development process, the system is used in the field after obtaining a stable version providing the designed features. During the tests in system development, the system is usually in a test environment and low number of microcontrollers used in the tests can be programmed individually with special programmers. Modifying the software is relatively easy because of low numbers during the tests. Even if stable software is obtained that meets the requirements of the system after the test phase, there are a lot of feedbacks when the system starts to be used in the field, and in this direction, it is necessary to update the firmware for the various bug fixes that are not noticed during the development of the software. In addition, various updates to improve the system efficiency and to give new features to the existing system are among the reasons that require changes to the software. Unlike the development and testing phases, it is not possible to modify the software with the methods used in the testing phase after the system is used by the end users in the field. The reason for this is that after the stabilized version is obtained, it is not commercially possible to program a plurality of systems distributed to end users as commercial products, or large number of microcontrollers forming a single system. In current commercial systems, the software update needs of almost all kinds of applications are met by bootloader software.

Bootloader software is an embedded software that starts from the fixed reset address of the microcontroller and it is designed to be as simple as possible in order not to make any changes on it in the future [1].

When the supply voltage is provided to the system or the system is reset, the bootloader application runs first and, if there is no update request depending on the design of the application, it jumps to the Firmware application which is located at a different memory address (Figure 1) and designed to meet the user's need. When the firmware update is requested, the firmware resets itself via an external command and switches to the bootloader [2]. The bootloader deletes the flash memory sectors of the existing

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Firmware and writes the program data of the new Firmware to the firmware address area from a predefined source, depending on the system design.

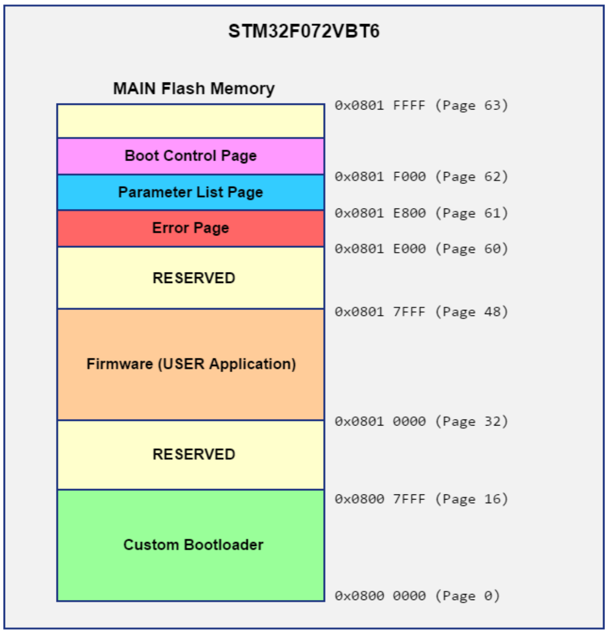

Figure 1. Memory map of one of the network elements in the system that shows the memory sectors of the bootloader and firmware.

After the bootloader writes all of the new firmware data to the corresponding address zone, the software will be used again by jumping to the firmware.

In this study, high-speed CAN Bus 2.0A protocol is used as the bootloader communication protocol. This communication protocol allows communication with 110 network elements at a maximum speed of 1Mbit / s over a total of 6.5 km [3]. The main reasons for using this protocol are as follows [4]:

1) The CAN bus protocol has a differential communication hardware so that it can operate smoothly in industrial environments with electrical noise.

2) Even if any network element connected to the CAN Bus network stops working, the network can continue to communicate without being affected.

3) The CAN bus protocol can operate as a Multi-Master. Each network element can have priority over the network when necessary.

4) Hardware prevention of the mixing of the similar priority messages that are sent by the network elements at the same time (Bitwise Arbitration).

5) The CAN Bus protocol has internal CRC (Cyclic Redundancy Check) in the message frame.

In addition to these, the reasons for choosing microcontrollers with ARM Cortex M0 architecture for the implementation of bootloader in the system are; reasonable price-performance values, 32-bit bus width, NVIC (Nested Vectored Interrupt Controller) hardware that allows flexible prioritization of the system interrupts [5], user friendly software development environments (KEIL, IAR, ATTOLIC vs.), easy findable software libraries for peripherals and some of the models in M0 series that have internal CAN Bus transceiver.

Similar to the designed system in this study, there are some bootloader designs for automobile ECU's (Engine Control Unit) developed on the 16 bit bus width NXP's Freescale MC9S12DP256 microcontrollers and that are using CAN Bus protocol [6]. ECU systems are one of the functional elements on the automobile which the software update is performed as a result of performance and efficiency improvements after the cars are produced and started to be used by end user. ECU software updates can be done through the communication line without removing the ECU component from the vehicle thanks to the developed systems. Another system developed for software updates of ECU components in the automotive industry is the software update system which incrementally updates the software by taking into consideration the differences between the old and the new program, rather than simply deleting or updating all program data for software updates [7]. In addition, similar to the designed system, there is also a system that updates a large number of ECU components on the CAN Bus communication line with a computer [8]. Except that, in addition to similar systems used in the automotive industry, there are also different bootloader and full-scale software update systems designed based on CAN communication protocol. An example of these systems is the software update system that enables the update of the embedded software of the DSP chips used in robotic systems to perform various control operations via the CAN communication line [9].

In this study, custom bootloader is designed to achieve software update feature for 32 bit bus width STMicroelectronics STM32F072 microcontroller. Also, it is aimed that the designed software update system can be used as a diagnostics mechanism by providing access to the desired parameters of the nodes of the distributed embedded system via the CAN Bus interface. The system is controlled by a computer via an interface device between the computer and the distributed embedded system communication network.

In Chapter 2, hardware information about the network elements used in the system, the user interface that allows the user to manage the system, the communication routines used in the system and the operating principle of the system are described. In Chapter 3, the observations of the system are explained and the contribution of the system is presented.

2. System Overview

The system consists of 3 types of components:

1) A PC which runs a graphical user interface (GUI) that allows the user to select which software to update the HEX file of the software that belongs to desired node to be updated.

2) A CAN Bus interface device which allows PC to communicate network nodes and the network elements.

3) Network nodes consisting of STM32F072 microcontrollers.

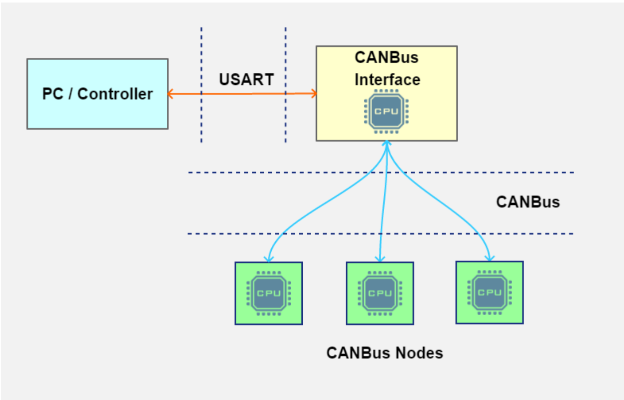

Figure 2. System communication scheme.

The PC and CAN Bus interface components exchange data with the USART protocol, and the CAN Bus interface component communicates with all network elements with the CAN protocol through the CAN bus network (Figure 2).

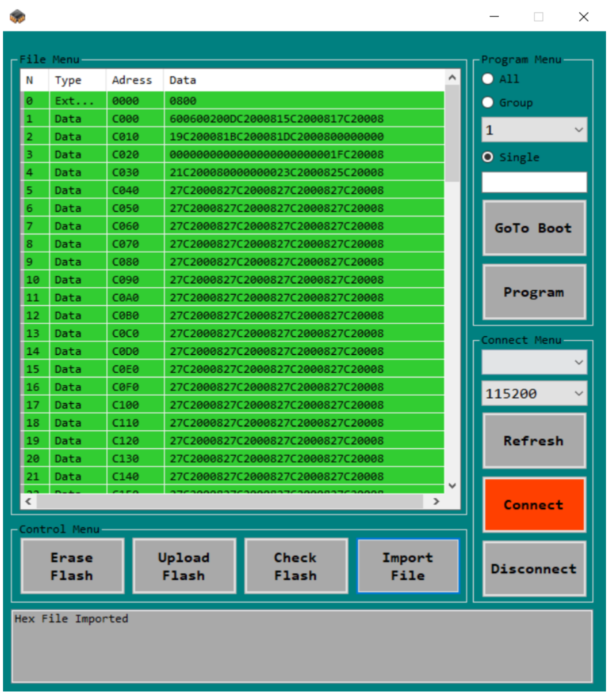

Figure 3. Graphical user interface on PC.

In order to update the embedded software of any network element on the CAN Bus network, the user first imports the HEX file of the new version of the firmware into the user interface application (Figure 3).

The graphical user interface program allows the user to update the firmware of the network elements on the distributed embedded system and inform the user about the success of the performed operations visually. The user can check the record type, the record address and all the data values of the HEX file lines with graphical user interface.

The HEX file uploaded by the user to the interface program is transferred to the flash memory of the Can Bus interface component which bridges the PC to the Can Bus network before programming the desired elements on the network. The main reasons of this transfer are, improving the software update time of the nodes and simplifying system message routines. Instead of using the CAN Bus interface component just for the message conversion between CAN and USART for every data message used in the programming process, the flash memory of interface component is used as a buffer to store program data. After saving the HEX data to interface component's flash memory, PC sends a program command to interface board. After CAN Bus interface board receives the program command message, it starts to send program data to desired node through CAN Bus network. Before each programming process, the user can check if the flash memory of the CAN Bus interface board is empty or not by using the graphical user interface on the PC. If the flash memory is full, user can also give command to the CAN Bus interface board to delete flash via the GUI.

The user can perform the software update process of the network elements in several different ways with the user interface on the PC. These ways are; entering each network element's individual network ID, entering the group ID associated with grouping the network elements and programming all the cards in sequence with a single command.

Each line of the HEX file loaded into the user interface contains the checksum data which is a control value specific for each line. The user interface application calculates the Checksum values for each line of the loaded HEX file and checks the validity of the file by comparing it with the control values in the lines of the HEX file and informs the user accordingly. In case of an error in any line of the uploaded HEX file, the corresponding HEX file line is indicated by red background color. After the valid HEX file is uploaded to the user interface, the HEX file of the Firmware is transferred to the Flash memory of the CAN Bus interface component by connecting to the interface component via USART with the valid Port number and Baud Rate.

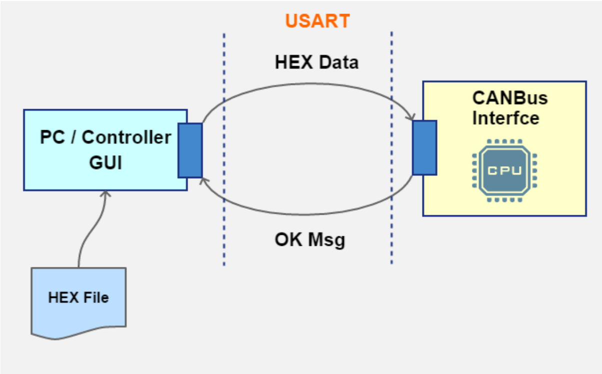

Figure 4. USART messaging schematic between PC and CAN Bus interface component.

Each line of the HEX file sent to the interface component as an USART message contains checksum information. The main reason of sending this checksum information in addition to HEX data is to make sure that the data is securely received by interface component. When the interface component receives the USART message for each HEX line, it calculates the control value using the relevant data and confirms the validity of the data by comparing it to the control data of the sent message. After this control, the received HEX data is written to the Flash memory of the interface component. When the received data are written to flash memory, flash record address value is also checked to ensure the writing process is successfully completed. If all of the control phases are passed, CAN Bus interface board sends the “OK” message to the PC through USART. All of these control phases and the message flows for single HEX value transfer defined as a single cycle of data transfer between PC and interface board (Figure 4). This routine is repeated for each HEX data until the last HEX data is sent. If an error occurs during the any line of HEX file transfer cycle, CAN Bus interface board sends the “ERROR” message to the PC and deletes its flash memory that keeps the HEX file data. When the GUI gets the “ERROR” message from the interface board, it stops the HEX file transfer and informs the user about the cancelled transfer routine. In addition, there is a threshold time defined for every HEX line transfer routine and if “OK” or “ERROR” messages are not sent by CAN Bus interface board before the threshold time, GUI considers the current HEX file transfer routine as unsuccessful and it informs the user about the cancelled transfer routine.

All of the elements on the CAN bus network in the system, have their own predefined 1 byte size network ID. These network IDs can be written to a specific flash address of the microcontroller while the bootloader is being loaded to each network element during production or can be defined with an 8-DIP switch hardware which can be located during the electronic card design.

After transferring all of the data in the HEX file to CAN Bus interface board’s flash memory, the user enters the network ID of the desired node to be updated via the GUI and presses the “GoTo Boot” button. After the user pressed the "GoTo Boot" button, GUI sends the "GoToBoot" message with the corresponding network node ID to the CAN Bus interface board. When CAN bus interface board receives that USART message from PC, it sends the “GoToBoot” message to the network element with the corresponding node ID given by the PC. Then the network element with the corresponding ID that is running on the firmware application writes a control value to the Boot Control Page address 0x0801F000 of the flash memory that is specified in Figure 1 and resets itself. After the reset, the bootloader application which is located on the start address of flash memory runs and verifies the value at the Boot Control Page address then it starts to erase the flash sectors of firmware application. When the interface board completes the deleting process, it sends the “BootOk” message to the CAN Bus interface board and starts to wait for CAN Bus data messages of the new firmware. This procedure is referred to as placing the network element in Boot mode. When the network element jumpes into the Boot mode and sends the “BootOk” message to the CAN Bus interface board, the user is informed about the network node that is ready for the update. If the network node does not send the “BootOk” message before the threshold time, the system considers this procedure as unsuccessful. After the desired network element is put into Boot mode, the user orders CAN Bus interface board in order to program the corresponding network element by pressing the Program button via the GUI on the PC.

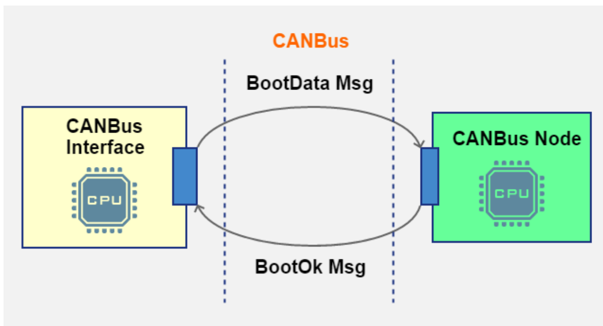

Figure 5. CAN messaging schematic between CAN Bus interface board and a network node.

Then the CAN Bus interface board starts to transfer the HEX data to network node with the “BootData” messages which contains the ID of the network node through CAN Bus. CAN Bus 2.0A message frame has an internal 16 bit wide CRC area. When a network message is received incorrectly even by just one node in the network, sender detects this fault with 2 bit wide ACK zone in the frame and resends the current message again. Difference from the USART data messages in the system, no control values are sent in the "BootData" messages because there is already an error checking mechanism in the message frame. After each "BootData" message arrives at the corresponding network element, the message content is written to the firmware area in the flash memory of the network element. After network node writes the received data to its flash memory, it checks the value of corresponding flash address then sends "BootOk" message to the CAN bus interface board (Figure 5). When the interface board reads "BootOk" message, it sends another "BootData" message that contains the next HEX data. This routine is repeated for every HEX data. After all of the HEX data has been successfully sent to the network element, a special "BootData" message that contains transmission complete value is sent as a last message. If the "BootOk" message is not received by the CAN Bus interface board before the threshold time, CAN Bus interface board considers the transfer operation as unsuccessful and it stops the HEX data transfer. Then it sends the "ERROR" message to the PC in order to inform the user. After the "BootData" message that contains transfer complete value is received by the network element, the network element deletes the Boot Control Page of the Flash memory and resets itself. After rebooting, the bootloader controls the Boot Control Page address and starts the updated user application by jumping to the Flash address of the firmware because the control data was deleted during the previous run. This whole procedure that starting at entering of the desired node ID and sending the Program command from the GUI is referred as programming of a single network device. But except from the Firmware update of single node, the user can update the Firmware of the all nodes or the Firmware of the groups that are consisting of multiple nodes with a single command. In order to program multiple nodes with a single command, the user can select the Firmware update mode by using the "All" and "Group" radio buttons on the GUI. When the "Group" mode is selected, the GUI sends the Program command to CAN Bus interface board for every node ID in the selected group in order and performs the same procedure as the single node Firmware update one by one. If an error occurs during the process, update process stops and the user is informed by GUI about the node ID that has not been programmed. When the "All" mode selected, same procedure is performed by the GUI same as the "Group" mode for all node IDs.

The flowchart of HEX data transfer from the CAN Bus interface board to a single network element is represented in Figure 6. When the interface board receives the Program command with the desired node ID from the GUI, it starts the transmit routine of the HEX data which is stored in the flash memory.

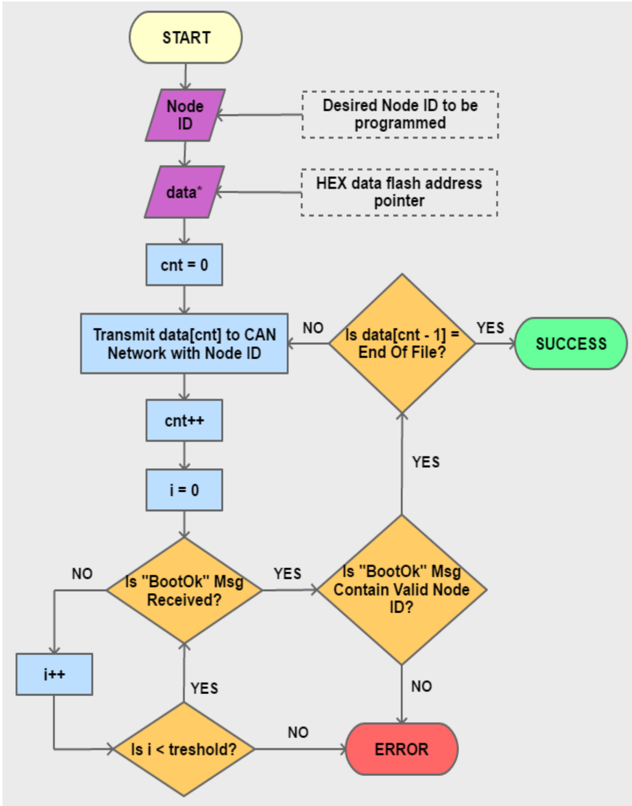

Figure 6. HEX data transfer from the CAN Bus interface board to a single network element.

The HEX data is represented with a pointer that addresses the starting address of the flash sector that contains the HEX file. The pointer value is incremented at every cycle of transmit routine and if the "BootOk" message is received until the threshold time, transmit routine continues until the last HEX data as mentioned before.

The message IDs used in the system are fixed for the Boot messages sent by the CAN Bus interface hardware but for all messages that is sent from the network elements, ID value is set to 0x20 + Network ID. That means the network IDs of the nodes can be understood from CAN Bus message IDs. The types of the messages that are sent from nodes are being sent inside the data frame of CAN Bus message as 1 byte. The reason for the use of variable message IDs according to the identity of the network element is to ensure that if multiple network elements send the same message at the same time, priority is given between the messages and, if desired, by a hardware filter to a particular ID group to ignore messages from these network elements by other network elements according to the design of the system.

3. Conclusions

The software update system has been implemented on an existing discrete embedded system that has high speed CAN Bus network and consists of 46 network elements. The embedded software of the network elements of the related system has been updated successfully without any errors. During the tests, the network elements were put into the Boot mode in order to be updated individually, in groups and all elements at the same time by the command that are sent from the computer.

In the programming process during the tests, the transmission of the 20 KB size HEX file which contains the updated firmware was completed by an average of 1.2 seconds for each network element by entering the network ID of each network element individually on user interface. Also during the programming tests with multiple network elements, transfer time of the same HEX file to all 46 network elements took about 50 seconds. Compared to the single network element file transfer mode, the average transfer time of one network element is faster in multiple transfer modes. The main reason is that in the multiple programming mode, the user interface informs the user only when an error occurs. Instead of informing user for every network element after the transfer is completed, this method uses the UART communication and GUI functions less than the single transfer mode.

In addition to software update processes, the computer was used to read and write the parameters of network nodes used on the current system. As a result of the test, it has been observed that the system can also be used as a fault diagnosis system in order to read predefined runtime errors of the network elements.

With the system designed in this study, complete firmware update system for distributed embedded systems with CAN Bus field network is provided for general purpose. Also with the custom bootloader that have been developed during the study, in application firmware update over CAN Bus feature is integrated to 32 bit STM32F072 microcontroller. In addition, depending on the distributed embedded system, if more computing power is needed in the future, the Cortex M0 network elements that are used in the system can easily be replaced with higher level Cortex M series microcontrollers.

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Six Sigma Methodology and an Application in the Textile Sector

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Abstract

In today's world of increasing international trade, companies are suggested to learn, implement and maintain new production techniques in place of traditional production systems in order to sustain their assets. In this approach, we have worked on "Six Sigma", one of the strongest components of these so-called systems. Within the scope of this study, Six Sigma and its application areas are investigated, and as a result of the obtained findings, six sigma applications have been made in the textile industry where the quality is desired to be improved. In the study, conducted by following the six sigma's DMAIC (Define, Measure, Analyse, Improve, Control) steps, using the detection tools such as SIPOC (Suppliers, Inputs, Process, Outputs, Customers) diagrams, measurement systems analysis, root cause analysis, determination of poor quality sources and improvement on the basic problem have been made. The variation of the strips from the card and cer machines in the plant created great quality problems. Before the six sigma project, the average coefficient of variation value of the card machines was 2.02. With this project, the average coefficient of variation value of the card machines is aimed to be reduced to 0.5-1.5 range. After the six sigma project, the average voefficient of variation value of the card machines was reduced to 1.03.

1. Introduction

Six Sigma anticipates to place customers at the center of production, to base all decisions on concrete data, to improve processes, to get success, and to achieve a systematic approach to the permanence of results. Since Six Sigma uses this methodology, it provides great benefits to the companies it employs and provides competitive advantages to these companies in the market.

Six Sigma is used by many companies in the world. According to Dave Cote, The Chief Executive Officer of Honeywell; there is more than one technical tool within powerful tools, an administrative and cultural exchange program. Using the DMAIC problem solving methodology consisting of Define, Measure, Analyze, Improvement and Control stages, Six Sigma is applied in many different areas today and very successful results are obtained. Six Sigma applications, as the basis for statistical thinking and statistical methodologies increase day by day [1].

Six sigma methodology is used in this project to improve the quality of production processes of a company operating in the textile sector and to meet customer demands. In the literature search section, information on Six Sigma strategy and methodology were given and explanations were made about the statistical techniques underlying the Six Sigma technique.

During the implementation phase of the workshop, application steps of Six Sigma (Define, Measure, Analyze, Improvement, Control) are followed and by the help of the solution development of Six Sigma technique is explained. The experimental results are analyzed by using the technical details used in the application. In the improvement phase, the solution approaches related to the problem are explained. The average Coefficient of Variation (Cv) value was reduced from 2.02 to 1.03 after improvements.

2. Literature Search

2.1. Six Sigma

Six Sigma depends on analyzing and developing all the processes in each operation. Systems always have

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opportunities for improvement. The main thing is to recognize these opportunities and to create systems that will evaluate these opportunities. The Six Sigma approach is a widely used technique to minimize losses in the industry, reduce costs, increase productivity and provide customer satisfaction. Six Sigma, a scientific approach, that is systematic, based on continuous improvement, removes the variability which creates the source of the questions, adopts goals and management, requires full participation, develops long-lasting solutions and provides continuous improvement. Six Sigma, as understood from the explanations, is a statistical method that keeps customer satisfaction in the foreground, mostly reduces the error rates, increases the performance and productivity. In other words, the method focuses on maximum internal and external customer satisfaction and superior achievement.

Six sigma methodology can be applied in almost all sectors, from telecommunications to manufacturing, finance, healthcare and entertainment [2]. The companies that implement the Six Sigma method follow the efficiency of their processes with an index called sigma level. Sigma expresses the standard deviation, which is a measure of variability in statistics, how much the process or processes of the organizations in the business life are variable, how much error it makes, or how much of the losses are [3].

2.2. The History of the Six Sigma Approach

Looking at the beginning of the historical development of Six Sigma, Americans were actively expanding their markets in the 79s. In response to market expansion of the Japanese, the answer came from Motorola. Starting in 1979, Motorola reviewed the costs of poor quality due to scrap, reprocessing and inspection. In the decade of the 80s, Motorola saw significant variability as an enemy, taking great steps in terms of quality and improvement with Six Sigma approach, achieving significant gains [4]. Bob Galvin, Chief Executive Officer of Motorola in 1987, made a plan; aiming to improve quality targets 10 times until 1989, 100 times improvement by 1991 and reaching Six Sigma sufficiency in 1992. Six Sigma competencies have been overcome by reaching an average of 5.4 sigma sufficiency in 1992 or 40 PPM and even going beyond it in some products and processes [5]. In the period of 1987-1992, manufacturing errors were reduced by 150 times with Six Sigma method and Motorola saved 2.2 billion dollars. Later, in the period of 1987-1996, it was announced by the authorities that the company saved $ 11 billion [4]. Six sigma method aims to reach perfection by acquiring only 3.4 percent failure in a million production. In the Six Sigma studies, it is assumed that the process will deviate from 1.5σ in the long term. This means that the average of the process is allowed to deviate from the average of 1.5σ to the left or right.

2.3. Six Sigma Organization

The success of Six Sigma depends on the well defined roles for everyone. For this reason, all the staff members of the Six Sigma organization are retitled and their job definitions are redefined [6].

2.3.1. High Quality Council

Senior management does not waste time learning about Six Sigma, if the most qualified personnel are not assigned for this job and if they do not provide the needed resources, projects will not have a chance to succeed. For this, it is essential to establish a top quality council, especially in large enterprises.

2.3.2. Champion

The Six Sigma champion is the person or people who observe the improvement projects on behalf of the top quality council. Among his main tasks are; to ensure that the remediation projects are consistent with the business objectives, to ensure coordination between the remediation teams and to set the overall goals of the projects [6].

2.3.3. Process Owner / Project Owner

In a company decided to make improvements by employing the Six Sigma, one of the senior executives is identified as Project owner. Tasks of the project owner; to assist the top management in selecting and evaluating the project, helping to identify the team members to be assigned important duties, preparing and implementing training plans [7].

2.3.4. Expert Black Belt

Expert Back Belt is a person who has the highest level of technical knowledge about the Six Sigma. Among the main tasks of the Expert Black Belt are to provide technical support to the improvement teams, in particular the selection and use of statistical methods, to assist the six sigma champions in determining the completion times of the projects.

2.3.5. Black Belt / Green Belt

They are the leaders of the improvement team. It is primarily responsible for the selection, implementation and conclusion of the improvement projects. By effectively using Six Sigma tools, they must be competent to bring fast and lasting solutions to business problems.

2.3.6. Team Members

They are the people who take part in the Six Sigma projects and provide the necessary support for the execution of the projects. When they support projects, they continue their operational duties. They need to have knowledge about Six Sigma philosophy, Six Sigma tools, basic measurement and analysis methods.

3. The Methodology of Six Sigma

Many methods are used in scientific improvement studies. However, it is known that all methods are based on the PDCA (Plan, Do, Check, Act) cycle developed by W. Edward Deming. The PDCA cycle includes planning, doing, checking, and acting precautionary measures, respectively [8]. In the case of Six Sigma, the DMAIC (Define, Measure, Analyse, Improve, Control) cycle consisting of the initials of the processes is used to optimize the processes. The difference in the DMAIC cycle, which is basically similar to that of the PDCA, is that it also evaluates the measurement and recovery phases separately. The expansion of the Six Sigma stages is explained below:

3.1. Identification Phase

During the identification phase, the scope of the project is determined together with the customer's needs and requirements. First of all, a detailed description of the problem is made and it is aimed to establish the team which will provide the highest success in solution of the problem in accordance with the project plan and the current plan. After defining the problem, the critical points of the project are identified. In this stage, SIPOC (Supplier, Input, Process, Output, Customer), cause-effect diagrams are used to analyze the current situation.

3.2. Measuring Phase

It is aimed to measure the current process in such a way as to cover all aspects and then to redesign the process by analyzing the data obtained therefrom. Before the measurement run is performed, it must be ensured that the measurement process does not involve any manipulation. This step of studying is very important because the information from the process will determine the continuing ability and capacity to uncover the product or service. In the measurement phase, a random sample can be taken from the data, and a different hundred percent measurement method can be followed, such as measuring all parts [9].

3.3. Analysis Phase

The analysis phase is the phase in which the data obtained when the validated measurement system is analyzed by various statistical tools. At this stage, data is determined by normal distribution tests to see if they have normal distribution. The effect on the result of the inputs determined in the identification and measurement phases is analyzed with appropriate statistical tools. The reduction of input factors and the determination of the highest influences on the outcome are carried out during the analysis phase.

3.4. Improvement Phase

It is the stage of the improvement activities for the reasons determined by the statistical results collected during the analysis stage. In order to optimize the outputs, the information about which inputs need to be focused is taken from the previous phase of analysis and necessary improvements are made. This is the stage at which the problem will be solved and its effects are reduced.

3.5. Control Phase

The control phase, the last step of Six Sigma, is the phase in which the continuity of the effect of the changes made is the result of the healing phase. At this stage, processes are standardized and controlled to ensure that the remedies are permanent and sustainable.

4. Six Sigma Application

4.1. Company Info

Çalık Denim, the first company of Çalık Holding, is among the top 10 premium denim producers in the world today. The company, which designs original denim collections with innovative approaches developed in the strong R & D center, serves the world's leading clothing companies such as H & M, Zara, Topshop and River Island. The company has adopted Six Sigma philosophy in recent years and aims to benefit from Six Sigma tools in its production processes. Within this scope, Six Sigma projects have been initiated. In this application, it has been tried to develop a solution to the quality problem by taking the support of top management and operating it. The application is explained in detail below.

4.2. Application

4.2.1. Identification Phase

Project Title: Reduction Coefficient of Variation (Cv) on card, cer and roving machines.

Problem Definition: Variation of Ne (Yarn Thickness) in strips produced in card and cer machines.

Problem: Because of Ne variation, it is the production of strips in different numbers.

The strips produced in different numbers due to the variation of Ne are described in Figure 1.

Figure 1. Strips produced in different numbers.

The 0.97 Ne and 0.105 Ne are undesirable thickness. The thickness required by the company should be 0.100 Ne.

Goal: The Cv values average of card machines is 2.02. Our goal is to reduce the average of Cv values to the standard operating range of 0.5-1.5.

The Sipoc diagram is the diagrams used to see an overview of the process that is considered to be improved in project work.

The Sipoc Diagram related to the process in which six sigma techniques are applied is given in Table 1.

Table 1. Sipoc diagram: cv difference map of cotton strip.

Suppliers	**Inputs**	**Process**	**Outputs**	**Customers**
Blending Department	Cotton	Compressing the cotton with pressure on the DFK machine (if the cotton DFK is not regularly compressed or fed properly, it will cause number differences.)	Homogeneous mixed cotton	Card Machine
Physics Department	Other Fibers	The cotton is opened in the card machine to become cheesecloth.	Cheesecloth	1.Passage Cer Machine
Card Department	Cheesecloth	After the cotton has been converted into a card strip, dubbing on the 1.passage cer machine (Thick and thin strips may occur because the 1.passage cer machines are not regulated.	Strip	2.Passage Cer Machine
Cer Department	Homogeneous strip	Cotton is regulated on the cer machine after dubbing. (Cv differences may occur due to regule problems.)	Regulated Strip	Roving Machine
Roving Department	Regulated strip	The strips coming out of the cer machine get twisted in the roving machine and get the roving	Roving	Ring Machine
Ring Department	Roving	The rovings produced in the roving machine take the yarn from the ring machine by taking shots and twisting.	Yarn	Bobbin Machine
Bobbin Department	Yarn	It is to wrap the irregularities of the yarns produced in the ring machine to the bobbins.	Bobbin	Fixing Machine
Fixing Department	Bobbin	To give strength to the bobbins coming out of the bobbin machine under suitable temperature and humidity	Ready to weave rope	Weaving looms

After the Sipoc Diagram was prepared, brainstorming took place with 8 people on the team. Brainstorming result 19 points scored. The improvement in the first 8 items according to the points of the scoring is left to the rest because it will be based on the investment in the company and this will cost too much to operate. It is aimed to improve by changing the existing one without moving the company in accordance with the six sigma philosophy and without incurring extra expenses. The points to be improved are designated as keys.

The main reasons of the problem and other reasons affecting the main reasons were determined. All these reasons are shown in the fishbone diagram in Figure 2.

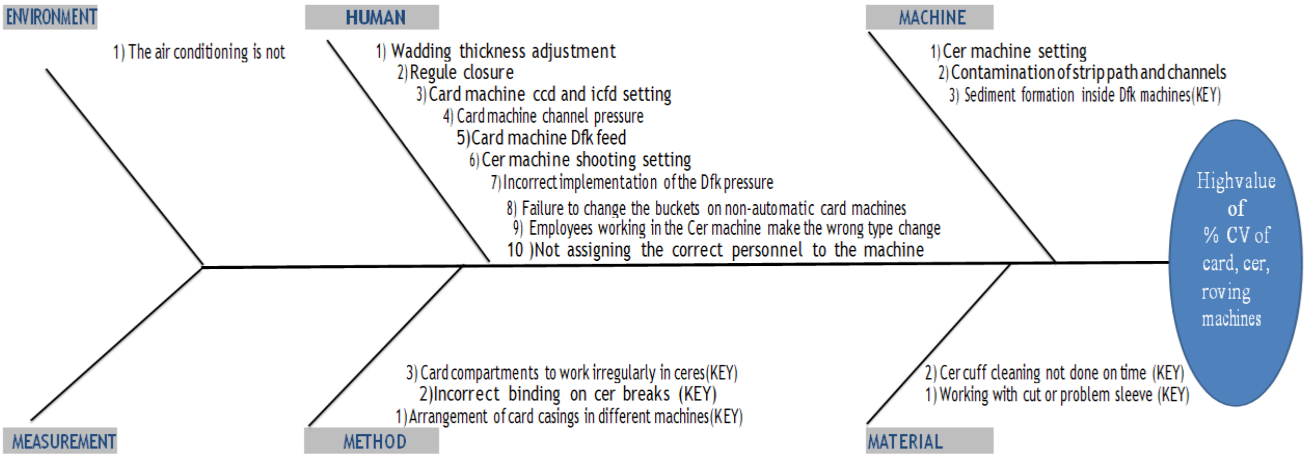

Figure 2. Fishbone diagram.

The problem is examined in detail and root-cause analysis is performed and the results are shown in Table 2.

Table 2. Root-cause analysis.

	CAUSES	CAUSE 1	CAUSE 2	CAUSE 3	CAUSE 4	CAUSE 5	ROOT CAUSE
HUMAN	Cer machine shots setting is corrupted	Excessive open areas due to mounting on the plant	Incorrectly set	Because the settings are made by the masters	Lack of education	Lack of maintenance	Lack of education
	Closing of card machine regulated	Excessive open areas due to mounting on the plant	Because the machine can not compensate	Because the number does not improve	The machine can not self-regulate	The feed is irregular.	The feed is irregular.
	Card machine wadding thickness adjustment disorder	Insufficient supply	Because the feeding table setting is not made	Lack of maintenance	Lack of education	Incorrectly set	Because the feeding table setting is not made
	Card machine channel pressure uncertainty	Pressure settings incorrectly entered	Because there is no standard work order	Lack of maintenance	Lack of education	Incorrectly set	Because there is no standard work order
	Card machine channel pressure uncertainty	There are leaks	Because the wicks are worn out	Lack of maintenance	Lack of education	Incorrectly set	Because the wicks are worn out
	Card machine DFK feed roller speed misalignment	Because it is assembled from different factories	Because some the card machine are old	Lack of maintenance	Lack of education	Incorrectly set	Because it is assembled from different factories
	Card machine ccd and icfd uncertainty	Sensor settings are corrupted	Lack of maintenance	Lack of maintenance team	Lack of education	Incorrectly set	Lack of maintenance
MACHINE	The cer machine's regulator setting is corrupted	Not regulated	Regule engine setting is incorrect	Because the machines are old and coal type	Lack of education	Incorrectly set	Because the machines are old and coal type
ENVIRONMENT	The air conditioning is not stable	Excessive open areas due to mounting on the plant	Because the air conditioning is old	Lack of maintenance	Lack of education	Incorrectly set	Excessive open areas due to mounting on the plant

The problem is examined in detail and the workflow of this process is shown in Figure 3.

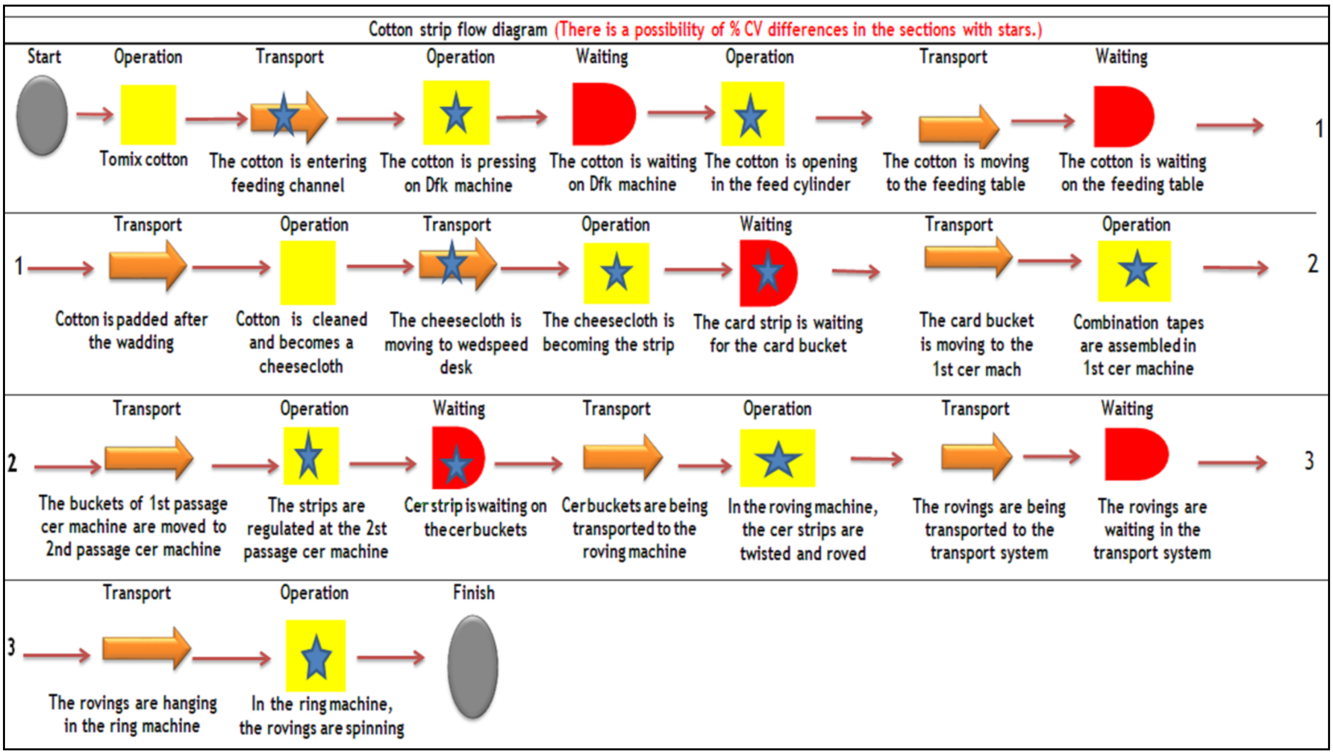

Figure 3. Cotton strip flow diagram.

The meanings of these signs are explained on the signs. These signs refer to operations, transporting and waiting operations. There is a high probability that Cv differences will occur in the sections with stars. The workflow of the process is explained with visual signs and the information about the stages of the process is transferred more easily.

4.2.2. Measurement Phase

The company has 72 cards in total. Cv values of 31 machines were examined within the scope of the project. Because the strips from these 31 machines were not of the desired quality. Strips were measured after the strips production was completed on each card. Based on these measurements, data was collected from machines that did not produce strips in the desired range. A total of 29 measurements were performed on 31 machines. The values obtained from the measurements are shown in Table A.1.

4.2.3. Analysis Phase

The measured values of each machine were entered into the minitab program and the standard deviation values were examined. When the machine Cv values were examined, 4 machines with the most variation were determined. The variations of these 4 machines and the average Cv values are shown in Figure 4.

4.2.4. Improvement Phase

The improvements made in the key points are explained below:

Improvements made within the scope of the project:

1. The Wadding Feeding Part pressure fixed to 300 and the balancing pressure was balanced at ± 5. Tires of the problem machines changed.
2. Cer gravitational cleaning procedure was made and improvement was achieved in practice by providing training on the correct fastening of detached roving strips.
3. Card machine measuring sensor for regulation adjustment in the feed cylinder setting 0.50; card machine measuring sensor for Cv waving in the output of the card machine has been set 2.75 and the settings were checked.
4. The card machine wadding feeding roller speed was measured and checked to be between the standard values of 5.1 and 5.3 rpm.
5. The wadding thickness adjustment was made between 55 and 70 and the feeding roller speed pressure was set to 600-800 pascal.
6. Cer muffs were recreated, a cleaning procedure was introduced, all the muffs were recreated, and a regular system was set up.

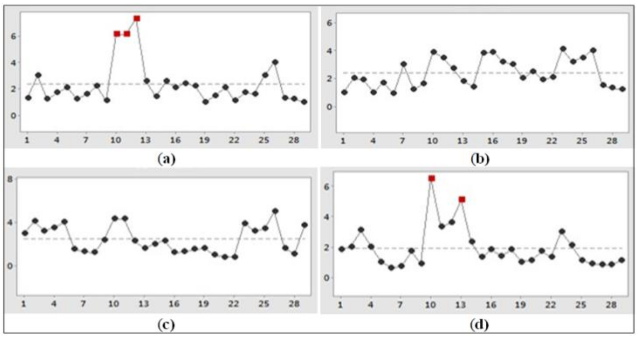

Figure 4. The average CV value of a-) the 25th machine was measured as 2.33 b-) the 26th machine was measured as 2.37 c-) the 32nd machine was measured as 2.45 d-) the 46th machine was measured as 1.92.

4.2.5. Control Phase

After the improvement phase, the data that we captured from 31 machines has been compared with the data that we had from the same 31 improvement machines. The results obtained from the improvements are explained in detail below.

The Cv values from 31 machines after improvements are shown in Table A.2.

The data of the 4 machines with the highest standard deviation value before and after the improvement is shown in the Figure 5-8.

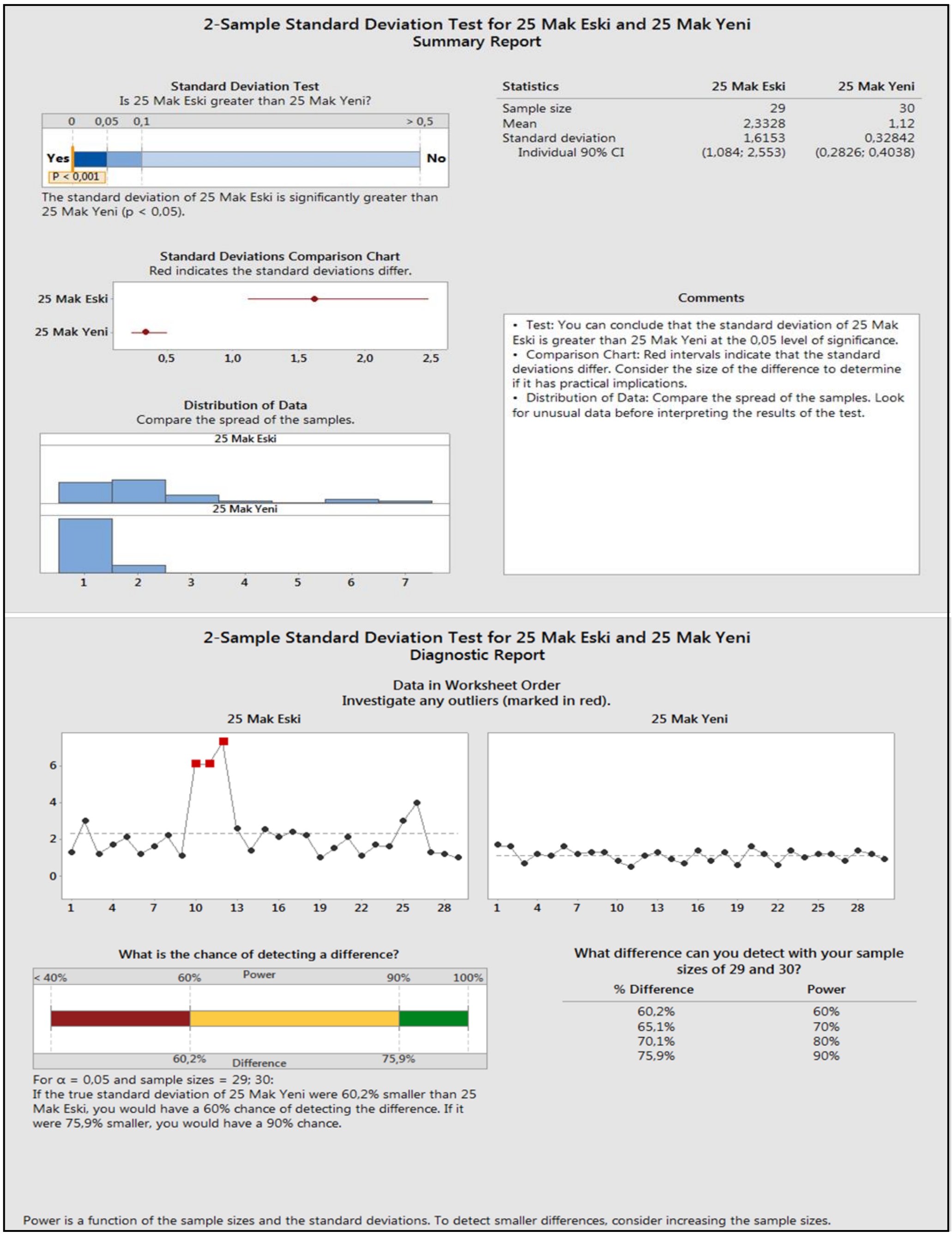

Figure 5. 25th machine's previous and next values.

Since the 25th machine P value is less than 0.05, we have achieved the statistical success. The average of the new Cv values of 25th machine is smaller than before, and the improvement of the new Cv values is observed. The average of the new standard deviation of 25th machine is smaller than before at the 0.05 level of significance. Red intervals in comprasion chart indicate that the standard deviations differ. Consider the size of the difference to determine if it has practical implications. In the distribution of data, compare the spread of the samples. Look for unusual data before interpreting the result of the test. Diagnostic report indicates that if the true standard deviation of 25th new value were 60.2% smaller than 25th before. We would have 60% chance of detecting the difference. If it were 75.9 smaller, we would have a 90% chance.

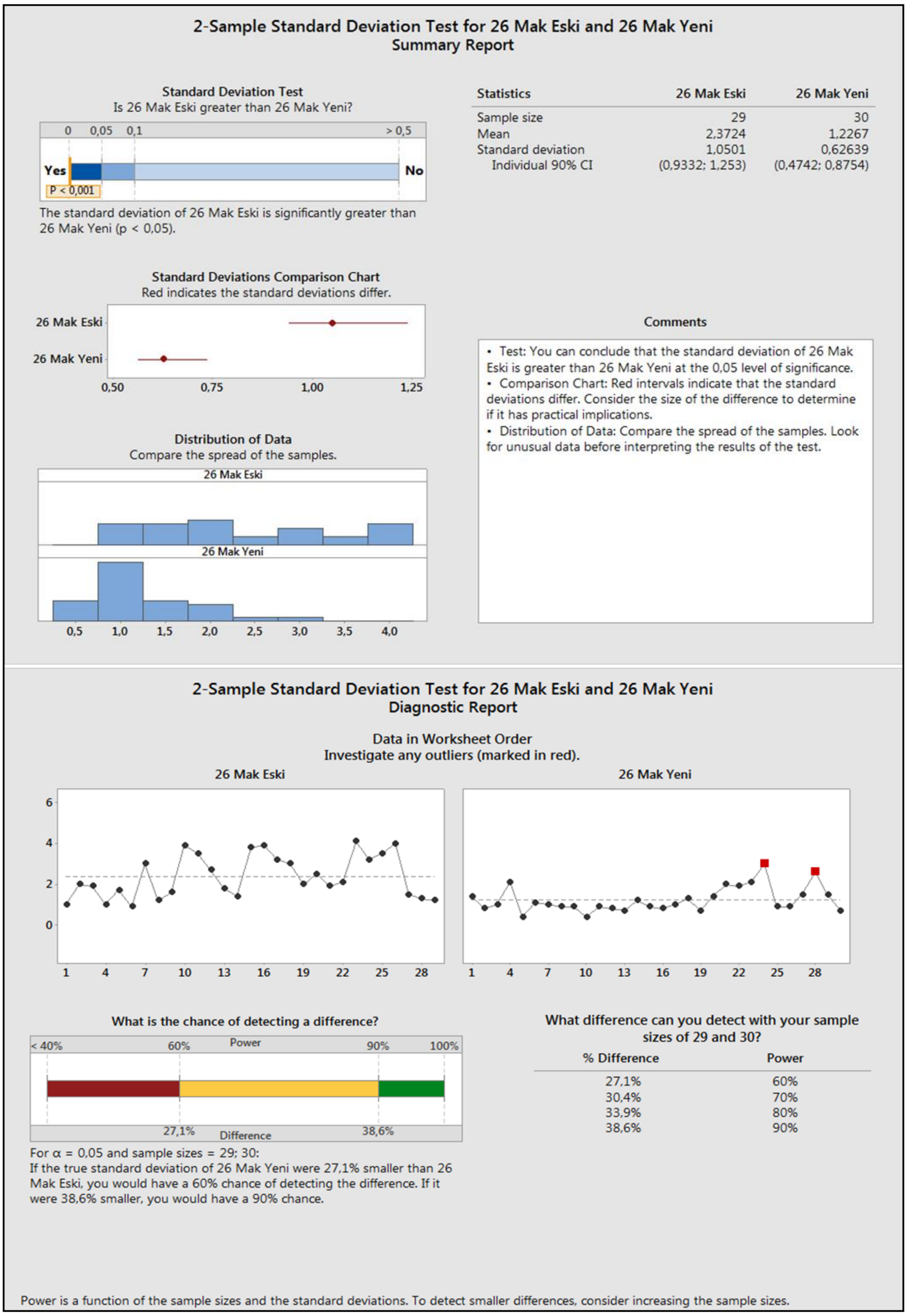

Figure 6. 26th machine's previous and next values.

Since the 26th machine P value is less than 0.05, we have achieved the statistical success. The average of the new Cv values of 26th machine is smaller than the previous, and the improvement of the new Cv values is observed. The average of the new standard deviation of 26th machine is smaller than the previous at the 0.05 level of significance. Red intervals in comprasion chart indicate that the standard deviations differ. Consider the size of the difference to determine if it has practical implications. In the distribution of data compare the spread of the samples. Look for unusual data before interpreting the result of the test. Diagnostic report indicates that if the true standard deviation of 26th new value were 27.1% smaller than 26th before. We would have 60% chance of detecting the difference. If it were 38.6 smaller, we would have a 90% chance.

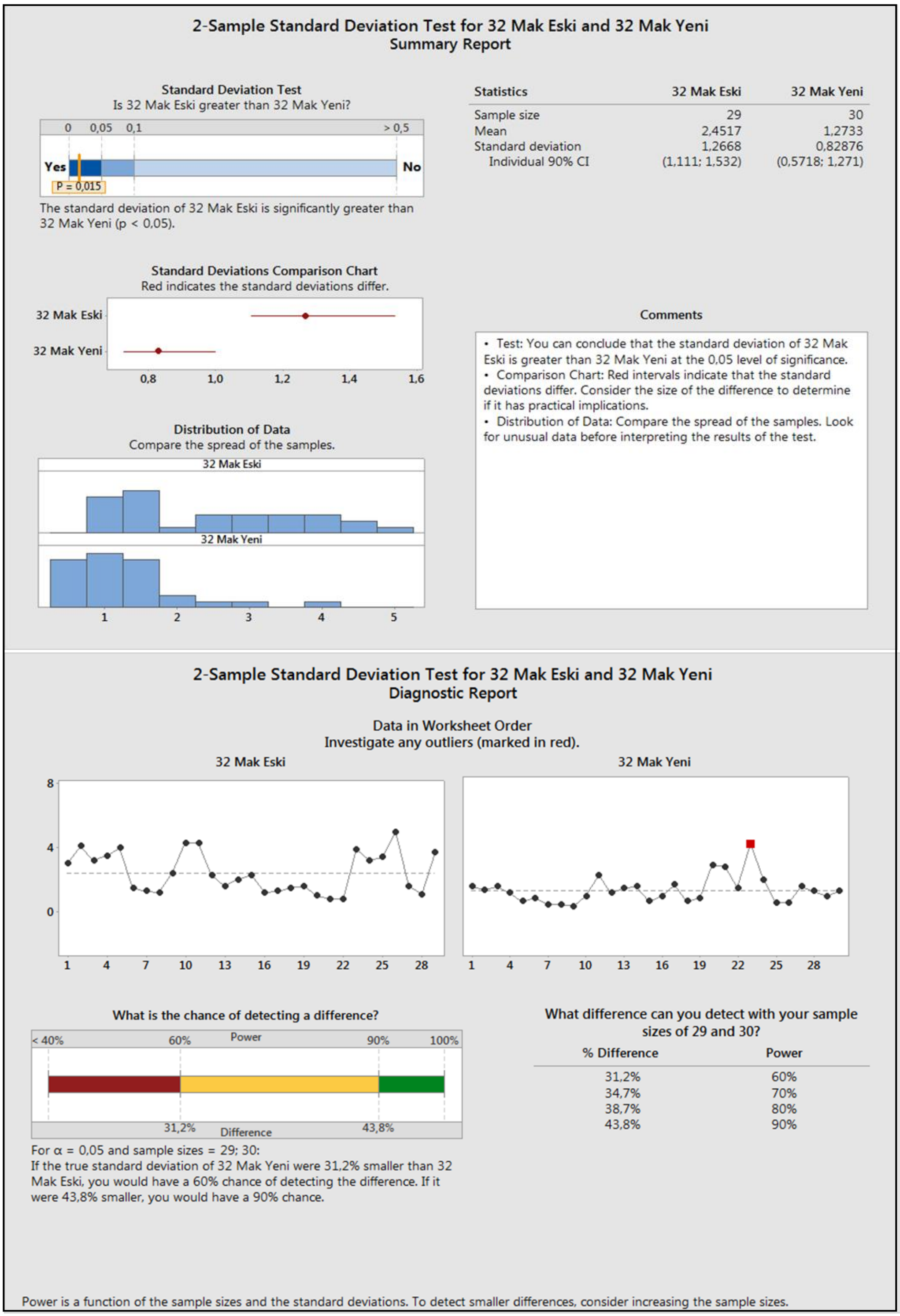

Figure 7. 32nd machine's previous and next values.

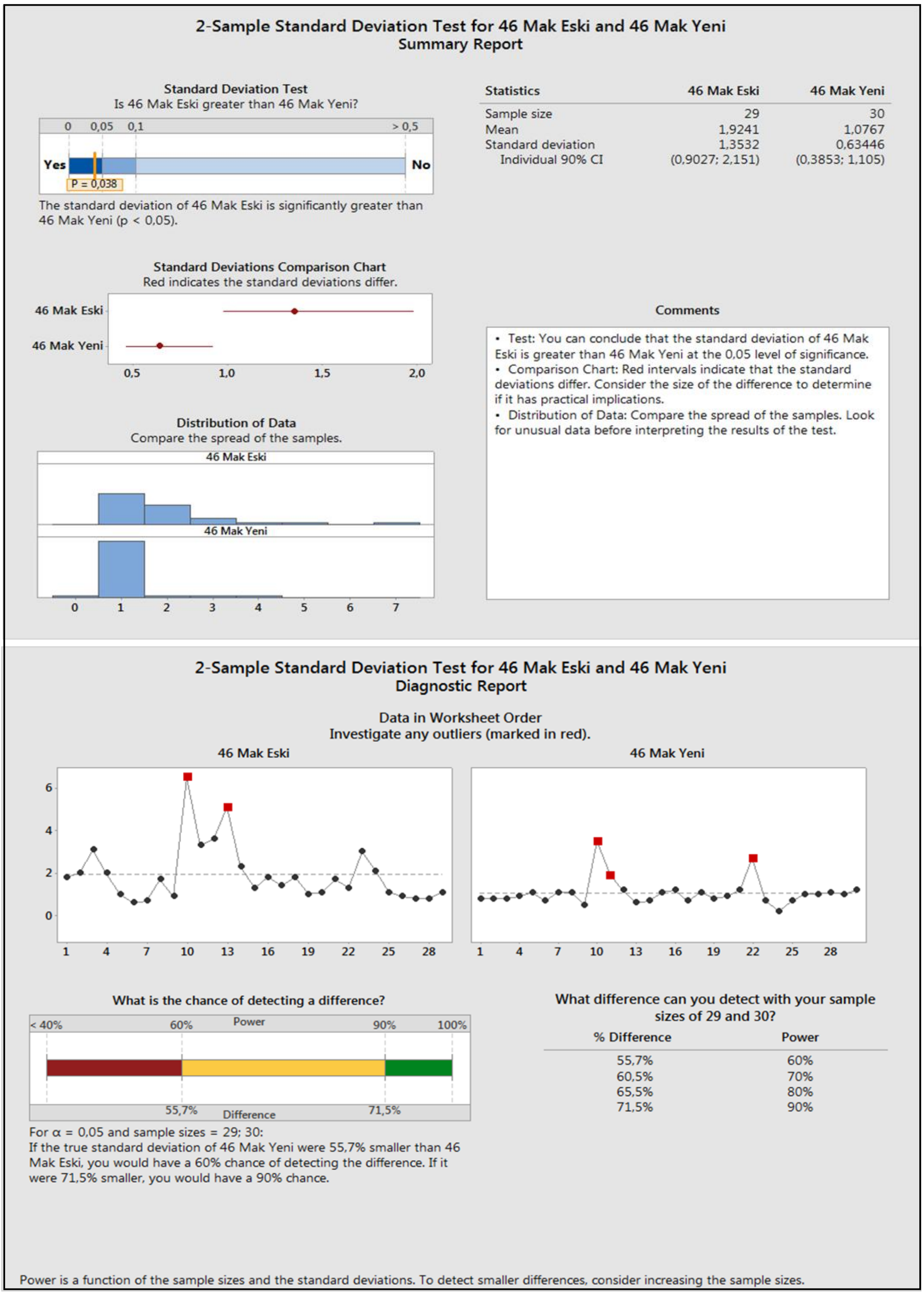

Figure 8. 46th machine's previous and next values.

Since the 32nd machine P value is less than 0.05, we have achieved the statistical success. The average of the new Cv values of 32nd machine is smaller than before, and the improvement of the new Cv values is observed. The average of the new standard deviation of 32nd machine is smaller than the previous at the 0.05 level of significance. Red intervals in comprasion chart indicate that the standard deviations differ. Consider the size of the difference to determine if it has practical implications. In the distribution of data compare the spread of the samples. Look for unusual data before interpreting the result of the test. Diagnostic report indicate that if the true standard deviation of 32nd new value were 31.2% smaller than 32nd before. We would have 60% chance of detecting the difference. If it were 43.8 smaller, we would have a 90% chance.

Since the 46th machine P value value is less than 0.05, we have achieved the statistical success. The average of the new Cv values of 46th machine is smaller than before, and the improvement of the new Cv values is observed. The average of the new standard deviation of 46th machine is smaller than the previous at the 0.05 level of significance. Red intervals in comprasion chart indicate that the standard deviations differ. It may be considered the size of the difference to determine if it has practical implications. In the distribution of the data, you could compare the spread of the samples and look for unusual data before interpreting the result of the test. Diagnostic report indicates that if the true standard deviation of 46th new value were 55.7% smaller than 46th before. We would have 60% chance of detecting the difference. If it were 71.5 smaller, we would have a 90% chance.

5. Results and Recommendations

The CVs on card, cer and roving machines differed outside of the desired standard ranges, an ongoing problem in the production process of the operator and an important point to focus on. This problem was challenging as one of the major problems that led to production disruption and yield losses. In this study, the definition and the size of the problem are clearly presented and the targets are determined. The study has been done to collect concrete data related to the process, and the root causes of the problem have been identified from this data. The process has been taken as a whole from the first operation in the work flow, the operators and masters in the operation are included in the project and the problem is solved by creating synergy.

According to the famous statistician Fischer, the maximum acceptable level of a fault should have been at 0.05. If the P value in a test is less than 0.05, it means that there is a significant difference in the comparison result. After the improvements in 4 machines with the highest standard deviation, P value of the data obtained from 4 machines was below 0.05. These values indicate that we have achieved the statistical success. Before starting the six sigma project, the CV value of the card machine was 2.02. As a target in the scope of the project, it is aimed that the card machine CV value average will be drawn to the standard range of 0.5-1.5. As a result of the improvements made, the average value of card machine CV value has been reduced to 1.03 and reached to the desired level. The improvement achieved after the project is described in Figure 9.

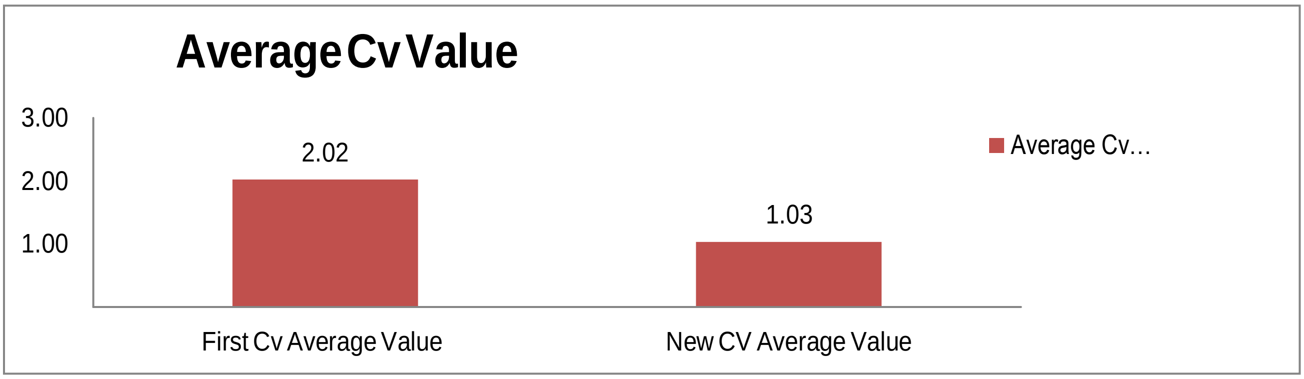

Figure 9. Previous and later average Cv values.

In this project, Six Sigma application in Çalık Denim company is shown with all steps. It is explained how to use the theoretical knowledge in the application phase, what to pay attention to in the application of each phase, how the data will be collected and evaluated in the Six Sigma process.

Acknowledgements

I also owe thanks to the members of the team who participated in the application project, Çalık Denim where the application project was made, and to the gratitude of continuous spiritual support throughout the process, mainly Black Belt Bülent ADIGÜZEL due to the contribution of my work in the application part.

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Appendices

Table A.1 and Table A.2 are shown on pages 19-20.

Table A.1. First Cv values (Machine no:1-15).

	First Cv Values														
Machine No	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
25	1.3	3	1.2	1.7	2.1	1.2	1.6	2.2	1.1	6.1	6.1	7.3	2.6	1.4	2.6
26	1	2	1.9	1	1.7	0.9	3	1.2	1.6	3.9	3.5	2.7	1.8	1.4	3.8
27	1.2	2	2	2	1.3	1.4	1.9	1.1	1.3	1	2.6	2.1	0.7	1.1	0.3
28	1.2	0.9	2	2.5	3	1.1	1.9	0.7	1.8	0.4	0.7	2.4	0.1	2.5	2.3
29	2	1.3	2	2.6	4	0.6	0.6	2	1.3	5.6	5.6	1.6	5.4	1.2	1.8
30	2	2.2	2.3	2.5	2	0.5	1	2.1	2.3	0.2	1.3	1.3	0.4	1.3	2
31	1.5	1.7	1.6	3	4	1.3	1.2	1	2.1	0.6	1	1	0.6	0.8	1.9
32	3	4.1	3.2	3.5	4	1.5	1.3	1.2	2.4	4.3	4.3	2.3	1.6	2	2.3
33	4	2.6	3.2	3.5	3	2	1.9	1	2.3	2.9	2.9	2.9	1.8	1.4	1.8
34	3.7	3.5	4.2	4.1	4	0.8	2.1	0.9	0.9	0.9	0.8	0.8	0.6	4.2	0.5
35	3.1	3.8	3.7	3.1	3.5	0.6	1.6	1.3	1	1.2	1.2	1.2	6.6	2.7	1.4
36	3	3	2	3.7	4	0.3	1.6	2	6.1	1.2	1.2	1.2	1.3	3.1	1.4
37	5	4.6	4.2	4.1	4.6	1.2	1.1	1.6	0.8	3.5	5.3	5.3	1.6	1.2	1.9
38	3.8	3.9	3.2	3.4	5	1.6	1.1	3.7	0	1	1	3.3	1.3	2.8	1.1
39	3.8	3.6	3.6	3.1	3.7	0.5	2.1	1.6	4.4	3.9	0.5	0.9	2.2	1.9	1.6
40	3.5	4.1	4.5	6	2	1	2.2	2.3	0	2.4	2.4	2.6	2.6	1.9	2.5
41	1	3.2	1	0.6	3	1.4	0.9	1.4	2.3	2.5	2.5	2.6	2.4	1.9	8.2
42	0.5	0.5	1.8	3	2	1.1	1.4	1.3	1.2	1	1.1	1.2	1.6	3	1.5
43	1.7	1.7	1.3	3	2.1	1.1	0.9	0.8	0.8	1.1	0.9	1.6	1.6	2.5	1.6
44	4	3.5	3	3.2	2.8	0.8	0.6	1.4	0.8	1.4	1.2	1.3	1.3	2.1	1
45	1.8	1.1	2	3	3.2	1.2	1.5	1.3	0.7	0.9	2.4	2.4	0.7	3	0.7
46	1.8	2	3.1	2	1	0.6	0.7	1.7	0.9	6.5	3.3	3.6	5.1	2.3	1.3
47	0.8	1.1	1.5	1.1	1	0.6	0.6	0.5	0.9	1.5	1.5	1.5	1.2	1.5	1.2
48	0.5	0.4	1	2	1.3	0.6	0.8	0.6	0.9	1.6	3.1	2.1	2	4	0.9
49	0.9	0.7	1.3	1.2	1.5	0.9	0.9	0.9	1.1	1.4	6	2.2	3	2	1
50	2.1	2.4	2.6	2.4	2	0.8	0.5	0.9	1.6	2	0.6	0.9	2	2.6	6.1
51	1.5	1.6	2.2	3	2	0.6	0.9	0.6	0.5	2.3	3	1.4	2.1	1.8	0.8
52	1.2	2	1.8	2.1	3	0.9	1.1	1.1	0.6	1.8	3	0.9	2.8	1.6	0
53	0.5	0.2	0.5	0.7	1	0.8	3.2	1.4	0.5	3.1	3.2	0.6	1.6	1.3	4.4
54	1.2	1.3	1.5	1.6	1	0.8	3	1.1	0.8	1.2	3	1.5	1.1	1.8	0
55	1.1	1.5	1.3	1.4	1.2	0.5	2	0.6	1.3	2.8	2	0.7	1.1	1.6	2.3

Table A.1. (Cont.) First Cv values (Machine no:16-29).

	First Cv Values													
Machine No	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
25	2.1	2.4	2.2	1	1.5	2.1	1.1	1.7	1.6	3	4	1.3	1.2	1
26	3.9	3.2	3	2	2.5	1.9	2.1	4.1	3.2	3.5	4	1.5	1.3	1.2
27	2.3	2.5	2	2	1.8	0.9	2.3	2.6	3.2	3.5	3	2	1.9	1
28	3.4	2	2.1	1.8	1.5	1.3	0.8	3.5	4.2	4.1	4	0.8	2.1	0.9
29	1.3	1.2	2	1.8	1.6	0.6	0.6	3.8	3.7	3.1	3.5	0.6	1.6	1.3
30	1.2	2	1.8	2.1	3	0.2	1.2	3	2	3.7	4	0.3	1.6	2
31	0.5	0.2	0.5	0.7	1	1.3	0.9	4.6	4.2	4.1	4.6	1.2	1.1	1.6
32	1.2	1.3	1.5	1.6	1	0.8	0.8	3.9	3.2	3.4	5	1.6	1.1	3.7
33	1.1	1.5	1.3	1.4	1.2	0.2	1.6	3.6	3.6	3.1	3.7	0.5	2.1	1.6
34	3.5	3.2	3.1	2	2	0.8	0.6	4.1	4.5	6	2	1	2.2	2.3
35	3.5	3	2.1	2	1.8	1.6	1.7	3.2	1	0.6	3	1.4	0.9	1.4
36	2.1	2.4	2.2	1	1.5	0.2	1.3	1.3	0.4	1.3	2	3.9	0.5	0.9
37	3.9	3.2	3	2	2.5	0.6	1	1	0.6	0.8	1.9	2.4	2.4	2.6
38	2.3	2.5	2	2	1.8	4.3	4.3	2.3	1.6	2	2.3	2.5	2.5	2.6
39	3.4	2	2.1	1.8	1.5	2.9	2.9	2.9	1.8	1.4	1.8	1	1.1	1.2
40	3.6	3.1	3.7	0.5	2.1	0.8	0.8	0.8	0.6	4.2	0.5	1.1	0.9	1.6
41	4.5	6	2	1	2.2	1.2	1.2	1.2	6.6	2.7	1.4	1.4	1.2	1.3
42	1	0.6	3	1.4	0.9	3.6	3.6	3.1	3.7	0.5	2.1	1.6	4.4	1.3
43	0.4	1.3	2	3.9	0.5	4.1	4.5	6	2	1	2.2	2.3	0	1.2
44	0.6	0.8	1.9	2.4	2.4	3.2	1	0.6	3	1.4	0.9	1.4	2.3	0.5
45	1.6	2	2.3	2.5	2.5	0.5	1.8	3	2	1.1	1.4	1.3	1.2	1.2
46	1.8	1.4	1.8	1	1.1	1.7	1.3	3	2.1	1.1	0.9	0.8	0.8	1.1
47	0.6	4.2	0.5	1.1	0.9	3.5	3	3.2	2.8	0.8	0.6	1.4	0.8	3.5
48	0.8	0.8	0.8	0.6	4.2	0.5	2	3	3.2	1.2	1.5	1.3	0.7	3.5
49	1.2	1.2	1.2	6.6	2.7	1.4	3.1	2	1	0.6	0.7	1.7	0.9	2.1
50	1.2	1.2	1.2	1.3	3.1	1.4	1.9	2.5	3.6	3.1	3.7	0.5	3.3	1.2
51	3.5	5.3	5.3	1.6	1.2	1.9	1.9	8.2	4.5	6	2	1	0.9	2.8
52	1	1	3.3	3.3	2.8	1.1	3	1.5	1	0.6	3	1.4	2.6	1.9
53	3.9	0.5	0.9	2.2	1.9	1.6	2.5	1.6	0.4	1.3	2	3.9	2.6	1.9
54	2.4	2.4	2.6	2.6	1.9	2.5	2.1	1	0.6	0.8	1.9	2.4	1.2	1.9
55	2.5	2.5	2.6	2.4	1.9	8.2	3	0.7	1.6	2	2.3	2.5	1.6	3

Table A.2. New Cv values (Machine no:2-16).

New Cv Values															
Machine No	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
25	1.6	0.7	1.2	1.1	1.6	1.2	1.3	1.3	0.8	0.5	1.1	1.3	0.9	0.7	1.4
26	0.8	1	2.1	0.4	1.1	1	0.9	0.9	0.4	0.9	0.8	0.7	1.2	0.9	0.8
27	0.9	1.3	0.3	0.6	1.2	0.3	0.4	0.7	1.5	1.3	1.2	1.1	0.4	0.6	1.2
28	0.5	0.3	1.4	0.8	1.3	0.7	0.5	0.5	1	1.1	1.1	0.9	0.7	1.2	0.7
29	0.6	0.9	0.9	0.2	0.9	0.7	1.2	1.1	0.9	1.1	1	0.9	0.9	1.4	1.1
30	0.3	1.2	1.2	0.3	0.7	0.9	1.1	1	0.7	2.4	0.9	0.6	1.1	0.8	1
31	1	1.4	0.6	0.5	0.6	0.8	1.4	1.9	0.6	1	0.8	1	0.8	1.5	0.7
32	1.3	1.5	1.1	0.6	0.8	0.4	0.4	0.3	0.9	2.2	1.1	1.4	1.5	0.6	0.9
33	1.1	0.8	1.3	0.6	0.9	0.6	0.2	0.1	0.2	1.8	1.2	1.2	1.2	0.8	0.6
34	1.2	1.1	2.1	0.8	0.9	0.4	0.7	0.1	0.9	1.7	1.1	0.7	0.5	0.9	1.3
35	1.3	0.7	1.8	0.4	0.7	0.5	0.6	0.6	1.4	1.5	1.1	0.7	0.7	0.9	0.8
36	0.8	1.3	0.6	0.6	0.9	0.3	0.5	0.7	1.1	2.6	0.9	0.9	0.9	1	0.6
37	0.9	0.8	1.3	0.7	0.5	0.8	0.8	1.2	0.5	2.3	1	0.6	1.1	1.3	0.4
38	0.7	1	2.1	0.3	0.6	0.7	0.3	1.2	1.3	2.2	0.7	0.8	1.3	0.7	0.8
39	0.8	1.2	0.6	0.3	0.8	0.5	0.2	1.4	1.8	2.1	0.9	1.1	1	0.8	1
40	0.4	0.9	1	0.5	0.3	0.3	1.1	0.8	1.7	1.4	0.9	1	0.6	0.8	1.2
41	0.5	0.7	0.7	0.8	0.9	0.9	0.8	1.4	1.8	1.7	0.8	0.7	0.8	0.8	0.6
42	0.6	0.5	0.9	0.6	1.4	1.1	0.6	1.3	1.2	1.5	0.6	0.9	0.7	0.9	0.5
43	0.8	0.7	0.8	0.9	0.9	1.2	0.9	0.8	0.9	0.9	1.1	0.5	1	1	0.9
44	0.8	0.8	0.7	0.8	0.6	0.9	1.1	1.4	0.8	1.5	0.7	0.7	1.2	0.5	0.7
45	0.7	0.8	0.7	0.8	1.5	1.1	0.9	1.7	0.6	0.9	1.1	0.9	0.9	0.7	0.8
46	0.8	0.8	0.9	1.1	0.7	1.1	1.1	0.5	3.5	1.9	1.2	0.6	0.7	1.1	1.2
47	0.9	0.8	0.8	0.8	0.6	0.9	0.9	0.6	0.9	1.1	0.7	0.7	0.7	1.3	1.1
48	0.8	0.5	0.7	0.8	0.8	0.5	0.9	0.9	0.8	0.7	1	0.9	1.1	0.9	0.9
49	0.5	0.5	0.5	0.9	0.9	0.7	0.8	0.9	0.6	0.9	1.2	1	1	0.8	0.9
50	0.8	0.8	0.9	0.6	0.5	0.9	1.1	0.6	0.5	0.7	1.1	0.6	0.9	0.9	0.5
51	0.6	0.5	0.4	0.5	0.9	0.9	0.6	1.1	1.1	1.1	0.5	0.9	0.7	0.9	1
52	0.5	0.9	1.3	0.8	0.8	1.2	1.1	0.6	1.2	0.9	0.7	1	0.8	0.7	1.6
53	0.5	1.1	0.9	0.6	0.6	1.1	0.9	0.8	0.7	0.7	0.7	0.8	0.7	0.8	0.8
54	0.6	0.5	0.4	0.9	0.9	0.6	1.1	0.9	1.2	0.9	0.6	0.5	1	0.9	1.2
55	0.5	0.5	0.4	0.6	0.9	0.8	0.6	0.8	0.8	0.9	0.5	1.2	0.9	1.1	0.8

Table A.2. (Cont.) New Cv values (Machine no:17-30).

New Cv Values														
Machine No	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
25	0.8	1.3	0.6	1.6	1.2	0.6	1.4	1	1.2	1.2	0.8	1.4	1.2	0.9
26	1	1.3	0.7	1.4	2	1.9	2.1	3	0.9	0.9	1.5	2.6	1.5	0.7
27	1.4	0.7	0.5	1.9	3.1	0.3	3.1	2.9	0.9	0.7	0.5	1.5	1.1	0.9
28	1	1.2	0.7	1.7	3.4	1.4	2.1	1.8	1	1.1	0.5	1	0.1	1.2
29	1.5	0.9	0.9	2.7	1.6	1.2	1.4	1	1.4	1.3	0.9	1.7	1.5	1.4
30	1.3	0.6	0.9	3.1	2	5.8	2.1	1.2	0.6	0.8	1.2	3.4	1.2	1.1
31	0.9	1.1	1	1.7	1.1	0.9	3.1	3.7	0.8	0.7	1.2	1.7	1.5	1.3
32	1.6	0.6	0.8	2.8	2.7	1.4	4.1	1.9	0.5	0.5	1.5	1.2	0.9	1.2
33	1.2	1.4	0.7	1.1	1.7	1.6	2.1	1.5	1.2	1.2	1.4	1.3	1.1	1
34	0.9	0.8	0.9	1.9	2.1	1.5	3.1	2.7	1.1	1.4	1.1	1.4	0.1	1.1
35	0.5	1	1	2.5	1.8	2.7	1.1	1.9	0.6	0.6	1.2	3.7	1.7	1
36	1.4	0.3	0.9	1.3	2.2	1.4	1	1.6	0.7	0.8	1.1	1.5	1.4	1.2
37	1	0.6	1.1	1.2	3.2	1.4	1	2.1	0.7	0.8	0.9	1.1	0.1	1.1
38	0.8	0.9	0.9	1	2.8	1.4	2.1	1.8	0.9	1	0.7	1.7	1.7	4.6
39	0.6	1.3	0.8	2.8	2.2	2	5.5	2.3	1.2	0.9	0.9	1.3	1.7	1.4
40	0.3	1.1	1.2	1.3	3.2	2.8	0.9	1.1	1	0.7	1.1	1.7	1.8	1.4
41	0.7	0.7	1	0.7	2.8	0.9	0.1	0.7	1	0.9	0.7	0.6	0.8	0.6
42	0.9	0.9	1	1	1.9	0.9	0.2	1.1	0.8	0.7	0.5	0.5	0.8	0.5
43	1.2	0.9	1	1.1	1.5	0.6	1	0.1	0.5	0.9	1	0.9	1	0.9
44	1.1	0.7	0.9	1.3	0.9	1.3	1.3	2.1	0.9	0.6	0.7	0.6	0.8	0.6
45	0.9	0.9	0.7	1.2	1	0.6	0.8	0.1	1.1	0.8	0.9	0.9	1.2	0.7
46	0.7	1.1	0.8	0.9	1.2	2.7	0.7	0.2	0.7	1	1	1.1	1	1.2
47	0.7	0.9	0.9	0.7	0.8	1.7	1.9	1.1	0.8	0.7	0.7	0.8	0.9	0.8
48	0.6	0.6	1	0.2	0.1	0.5	0.1	1	0.8	0.7	0.5	0.7	0.7	0.5
49	0.6	0.8	0.9	1.8	1.2	0.7	1	1.2	1.1	1.2	1.1	1.4	0.9	0.7
50	0.9	1	1	1.9	1.9	0.8	1.2	1.3	0.7	0.6	0.7	0.7	0.7	1.3
51	0.9	0.6	0.7	1.2	0.7	1.5	1.3	0.9	0.9	0.9	0.5	0.5	0.4	0.4
52	0.7	0.9	0.8	0.7	1.2	0.9	1	0.7	0.8	0.8	0.8	1.2	0.6	0.7
53	0.9	0.8	0.7	1.6	1.3	1.1	1.4	1.1	0.9	0.7	0.9	0.8	0.9	0.9
54	1.1	1.1	1.1	0.3	0.9	1.6	1.5	1.2	0.9	0.9	0.5	0.5	0.5	0.8
55	0.9	0.7	1.2	1.3	0.1	0.9	1	0.2	1	0.7	0.5	0.5	0.6	0.5

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Variable-Speed Direct-Drive Permanent Magnet Synchronous Generator Wind Turbine Modeling and Simulation

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Abstract

In this study, the importance, the position, and the encouragements of wind energy which is a type of renewable energy in the world and in Turkey have been mentioned briefly. Also, wind turbines which have lost their importance from past to present and have been used today are discussed concisely. As the main topic of the study, the Permanent Magnet Synchronous Generator (PMSG) Direct Drive Wind Turbine has been mathematically modeled, and Back-to-back power converter was used and controlled. Then, findings of the study were supported by simulation.

1. Introduction

In recent years, the demand for energy has increased quickly with the increasing of the World population and the searches for new alternative energy sources instead of the decreasing fossil fuels has become a necessity besides their popularity. Renewable energy sources are cleaner and less harmful in terms of environmental aspects and, it is also known as Green Energy in literature. In Turkey, according to the ratio of the domestic production parts, the unit price of energy purchase has been increased and the investors and industrialists are encouraged in addition to the energy purchase guarantee with the Renewable Energy Resource Support Mechanism (YEKDEM). The wind energy is the kind of renewable energy, it is defined as in [1]; the sun is not being able to warm the atmosphere and the ground surface homogeneously. As a result, hot and cold air displaced and it caused flow in air by temperature and pressure difference.

The wind energy has been used to grind grain in mills, pump water, and generate electrical energy from past to present. The speed of the wind and air density effectuates a kinetic energy in the wind and this kinetic energy is converted first to mechanical energy then electrical energy. Generally, energy conversion is made by wind turbine and generator, being the two indispensable main elements in energy conversion. In addition to these, wind farms are formed in such a way that the cost is most suitable considering the elements such as gearbox, converter, hydraulic unit, lubrication unit, cooling unit, transformer, etc. the requirement, advantages and disadvantages of the current conditions.

From past to present, some wind turbines have lost significance. These are; according to axis type, vertical axis turbines; according to speed, fixed speed turbines; according to generator type, Direct Current (DC) generators and squirrel cage induction generators (SCIG). Instead of them, according to axis type, horizontal axis turbine, according to speed, variable speed turbine; according to generator type, doubly fed induction generators (DFIG), wounded rotor induction generators (WRIG), wounded rotor synchronous generators (WRSG), and permanent magnet synchronous generators (PMSG) are used along with developing technology, it implements

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reduced costs and provided high performance and efficiency.

In this study, Direct Drive Permanent Magnet Synchronous Generator Wind Turbine was modeled and full scale Back-to-Back converter was controlled by Space Vector Pulse Width Modulation technique. Previous publications related to PMSG based variable speed wind turbine were mostly modeled by power coefficient. In fact, the turbine transmits torque to the generator and in this paper the modeling was done by torque equations instead of power and the results were verified to torque coefficient figure. Finally, the optimum torque control was implemented to assure that the tip speed ratio was constant and maximum at low wind speeds as well. By this means, the maximum power provided to grid will only depend on wind speed. This study was also supported by simulation results.

2. System Modeling

In this paper, Direct Drive PMSG Wind Turbine energy conversion principle scheme is shown in Figure 1.

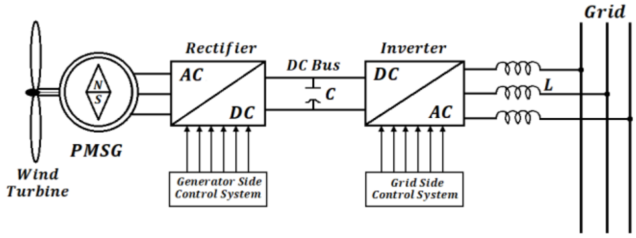

Figure 1. Direct drive permanent magnet synchronous generator wind turbine energy conversion principle scheme.

The PMSG used in the system is directly connected to wind turbine shaft without the gearbox, consequently gearbox losses and maintenance requirements are eliminated. The presence of permanent magnets instead of excitation windings in rotor of PMSG eliminates excitation losses in generator and it operates under high torque with its multi-pole structure and slow rotor speed. The control of magnetic flux cannot be carried out directly for the reason that the PMSG does not have an excitation winding such as wound rotor synchronous generators. Therefore, the control is made with full scale Back-to-Back power converters (DC bus existing) or matrix converters (DC bus not existing) designed as using improved semiconductor technologies.

The model of PMSG without damper winding has been developed on rotor reference frame using the following assumptions:

- Stator windings are sinusoidally distributed.
- The back-emf is sinusoidal.
- Eddy currents and hysteresis losses are negligible.
- Magnetic saturation is neglected.

While performing simulation, program MATLAB/ Simulink was utilized and “ode45” was used as the solution method.

2.1. Direct-Drive Wind Turbine Model

The power equation of wind because of kinetic energy rule due to movement of the wind is given as Eq. (1) [2, 3]:

$$P_{wind} = \frac{1}{2}\,\rho\, A\, v_{wind}^{3} \qquad (1)$$

where; P_{wind} (W) wind power, ρ (kg/m^3) air density, A (m^2) swept area by blades, v_{wind} (m/s) wind speed.

However, converting all of the power taken from the wind into mechanical power is not possible. According to Betz Limit, maximum efficiency of converting is defined in Eq. (2) as below [2, 4]:

$$C_{P_{max}} = \frac{16}{27} = 0{,}59259 = \%59{,}26 \qquad (2)$$

This equation identifies Betz Limit, and is shown as C_P coefficient. C_P value varies according to tip speed ratio and pitch angle and it is not a constant value. Therefore, the Eq. (3) is composed according to generated power by wind turbine by using Eq. (4):

$$P_{turbine} = C_P(\lambda,\beta)\,\frac{1}{2}\,\rho\, A\, v_{wind}^{3} \qquad (3)$$

$$\lambda = \frac{v_{linear}}{v_{wind}} = \frac{\omega_{turbine}\, r}{v_{wind}} = \frac{\frac{2\pi\, n}{60}\, r}{v_{wind}} \qquad (4)$$

where; λ tip speed ratio, β (degree) pitch angle, v_{linear} (m/s) linear velocity, $\omega_{turbine}$ (rad/s) shaft angular speed, n (rpm) revolution per minute, r (m) blade length.

C_P coefficient is calculated as in Eq. (5) by using Eq. (6) [5,6]:

$$C_P(\lambda,\beta) = C_1\left(\frac{C_2}{\gamma} - C_3\beta - C_4\right) e^{\frac{C_5}{\gamma}} + C_6\lambda \qquad (5)$$

$$\gamma = \left(\frac{1}{\lambda+0{,}08\beta} - \frac{0{,}035}{\beta^3+1}\right)^{-1} \qquad (6)$$

The mechanical torque generated by turbine is transmitted to generator. Thus, torque composes rotational movement in generator.

Torque equations are shown in Eq. (7), Eq. (8), Eq. (9), Eq. (10):

$$T = \frac{P}{\omega} \quad (7)$$

$$T_{turbine} = C_P(\lambda,\beta)\,\frac{\frac{1}{2}\rho\, A\, v_{wind}^3}{\omega_{turbine}} \quad (8)$$

$$T_{turbine} = C_P(\lambda,\beta)\,\frac{\frac{1}{2}\rho\, A\, v_{wind}^3}{\frac{\lambda\, v_{wind}}{r}} \quad (9)$$

$$T_{turbine} = \frac{C_P(\lambda,\beta)}{\lambda}\frac{1}{2}\rho\, A\, r\, v_{wind}^2 \quad (10)$$

where; $T_{turbine}$ (Nm) generated torque by wind turbine.

C_P power coefficient can be expressed as C_T torque coefficient. If an equation defines such as in Eq. (11):

$$C_T = \frac{C_P}{\lambda} \quad (11)$$

Obtained equation put into the Eq. (10) and rearranged in equation, the Eq. (12) can be acquired as:

$$T_{turbine} = C_T(\lambda,\beta)\,\frac{1}{2}\,\rho\, A\, r\, v_{wind}^2 \quad (12)$$

The parameters varied from C_1 to C_6 are design parameters of turbine and vary according to turbine. Figure 2 shows torque coefficient by various tip speed ratio and pitch angle.

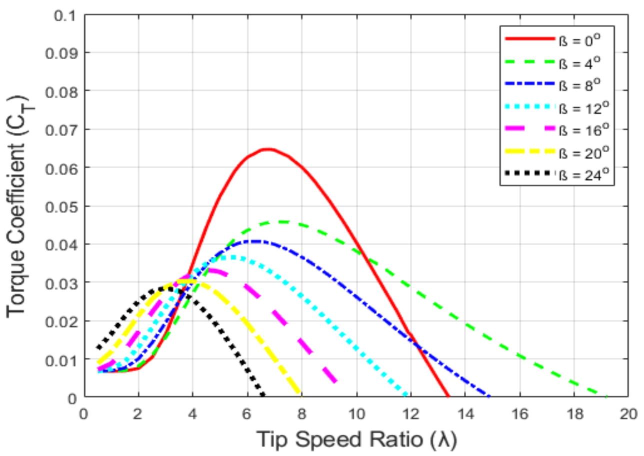

Figure 2. Tip speed ratio and torque coefficient according to pitch angle (c_1 = 0,5176; c_2 = 116; c_3 = 0,4; c_4 = 5; c_5 = 21; c_6 = 0,0068).

2.2. Permanent Magnet Synchronous Generator

The equations of PMSG in dq reference frame, obtained by park transformation are given in Eq. (13) and Eq. (14) by permanent magnets instead of excitation windings in the rotor [7]:

$$U_d = Ri_d + L_d\frac{d\,i_d}{dt} - \omega_e L_q i_q \quad (13)$$

$$U_q = Ri_q + L_q\frac{d\,i_q}{dt} + \omega_e L_d i_d + \omega_e \phi_r \quad (14)$$

where; U_d, U_q (V) stator dq reference frame voltages, i_d, i_q (A) generator dq reference frame currents, L_d, L_q (H) stator dq reference frame inductances, R (Ω) stator resistance, ω_e (rad/s) electrical angular speed, ϕr (Vs) flux linkage.

Arranged electromagnetic torque of PMSG equation is given in Eq. (15) [7]:

$$T_e = \frac{3}{2}p\left(\phi_r i_q + (L_d - L_q) i_d i_q\right) \quad (15)$$

where; T_e (Nm) electromagnetic torque, p pole pairs.

3. System Controlling

3.1. Generator Side Converter Control

The generator side converter transmits non-fixed frequency current generated in PMSG, into the DC bus. Therewithal, it controls the speed of rotor by field oriented control that provides high performance. Electromagnetic torque occurred in generator is generated by I_q current which is transformed to dq reference frame by park transform.

The generator side converter dq frame reference voltages are given in Eq. (16) and Eq. (17):

$$u_d^* = \left(k_p + \frac{k_i}{s}\right)\left(i_d^* - i_d\right) - \omega_e L_q i_q \quad (16)$$

$$u_q^* = \left(k_p + \frac{k_i}{s}\right)\left(i_q^* - i_q\right) + \omega_e L_d i_d + \omega_e \phi_r \quad (17)$$

The detailed concept of the used 6 pieces Insulated Gate Bipolar Transistors (IGBT) Back-to-Back converter of generator side is shown in Figure 3.

The Proportional Integral (PI) controller made closed-loop control by fault current between generator current and reference current. The IGBTs are triggered by Space Vector Pulse Width Modulation (SVPWM) technique through obtained reference voltages. The parameters of PI controller are adjusted by tuning method.

3.2. Optimum Torque Control

The speed of rotor can be controlled by the optimum torque control. If inductance of generator where L_d and L_q are equal, the equation is expressed in Eq. (18):

$$T_e = \frac{3}{2} p \phi_r i_q \quad (18)$$

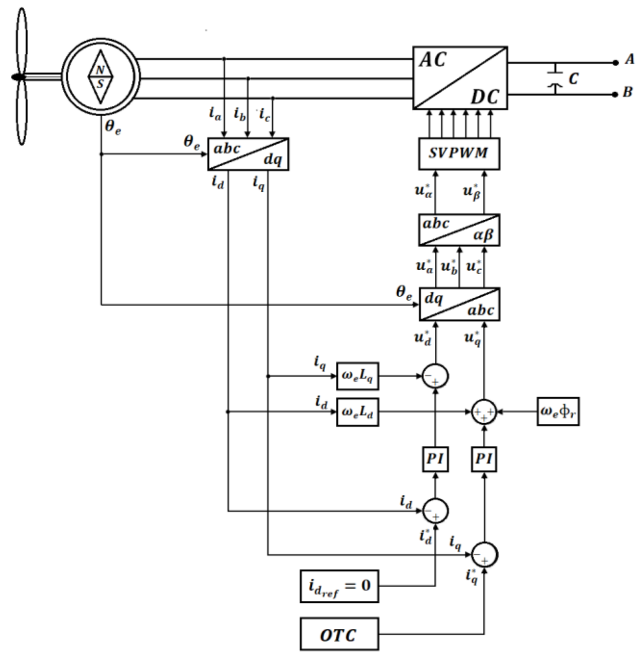

Figure 3. Generator side converter control scheme.

The electromagnetic torque in generator and I_q current are linear between each other. I_q reference current can be calculated by optimum torque control method.

With reference to this method, if the tip speed ratio is chosen as optimum, the value of C_T torque coefficient can be achieved. Herewith, the constant values for turbine are obtained and it is given as K_{opt} constant in Eq. (19) [8]:

$$K_{opt} = \frac{1}{2} \frac{C_T(\lambda_{opt}, \beta) \rho \pi r^5}{\lambda_{opt}^2} \quad (19)$$

If the requirement arranges are done, the following Eq. (20) can be obtained:

$$T_{opt} = K_{opt} \omega_{turbine}^2 \quad (20)$$

where; T_{opt} (Nm) optimum torque.

If the optimum torque and occurred electromagnetic torque in generator are equalized, I_q reference current can be acquired.

3.3. Pitch Control

The shaft of wind turbine must rotate in a permitted speed range to avoid mechanical stresses and damages in turbine and generator. Such as seen in Figure 4 the turbine operates between cut-in speed and rated wind speed at partial power, and it operates at full power between rated wind speed and cut-off speed. The turbine is at stand-by position when wind speed is less than cut-in speed and higher than cut-off speed. Generally the pitch angle of blades is 0 degree when the turbine is parking. The pitch angle varies when the wind speed is higher than rated wind speed in order to protects the turbine, and the rotor speed becomes stable [9].

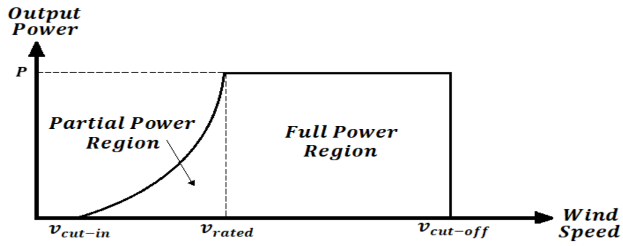

Figure 4. Power curve and pitch control according to wind speed.

3.4. Grid Side Converter Control

The generator side converter, converts DC voltage to grid frequency and Alternative Current (AC) voltage of grid, and it provides active and reactive power to grid. In the meantime, DC bus voltage is fixed by voltage oriented control.

The output voltages of converter dq reference frame equations are given in Eq. (21) and Eq. (22):

$$U_d = V_d + Ri_d + L\frac{d\, i_d}{dt} - \omega L i_q \quad (21)$$

$$U_q = V_q + Ri_q + L\frac{di_q}{dt} + \omega L i_d \quad (22)$$

where; U_d, U_q (V) dq reference frame converter output voltages, i_d, i_q (A) dq reference frame converter output currents, V_d, V_q (V) dq reference frame grid voltages, R (Ω) resistance of grid-transformer-filter, L (H) inductance of grid-transformer-filter, ω (rad/s) angular frequency of grid.

The provided active and reactive power can be shown as Eq. (23) and Eq. (24):

$$P_{out} = \frac{3}{2} V_d i_d = V_{dc} I_{dc} \quad (23)$$

$$Q_{out} = -\frac{3}{2} V_d i_q \quad (24)$$

where; P_{out} (W) provided active power to grid, Q_{out} (VAr) provided reactive power to grid, V_{dc} (V) DC bus voltage, I_{dc} (A) DC bus current.

This provides active and reactive power to grid, through under controlling stability of DC bus [10].

The grid side of space vector PWM voltage control strategy is shown as follow in Eq. (25-26):

$$u_d^* = \left(k_p + \frac{k_i}{s}\right)\left(i_d^* - i_d\right) - \omega L i_q + V_d \quad (25)$$

$$u_q^* = \left(k_p + \frac{k_i}{s}\right)\left(i_q^* - i_q\right) + \omega L i_d \quad (26)$$

The parameters of grid are given in Table A.2 as appendix and the detailed concept of Back-to-Back converter used 6 pieces IGBTs of grid side is shown Figure 5.

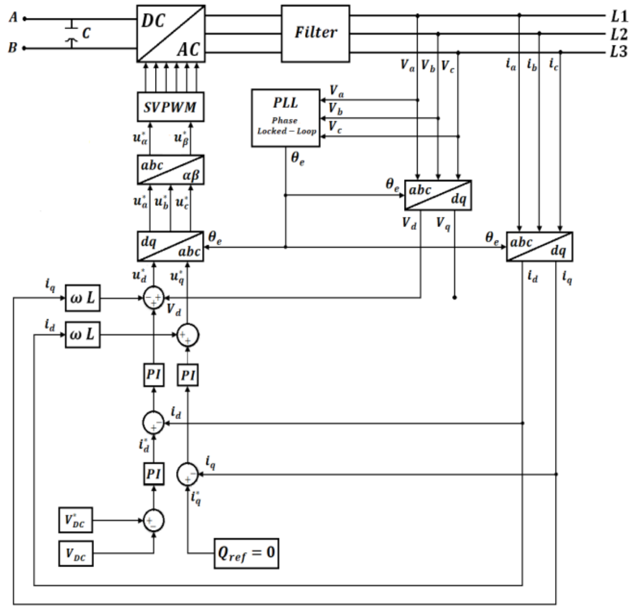

Figure 5. Detailed concept of grid side converter control scheme.

The PI controller is alike the generator side control, it made closed-loop control by fault current between generator current and reference current. The IGBTs are triggered by SVPWM technique through the obtained reference voltages. The parameters of PI controller are adjusted by tuning method.

4. Simulation Results

As a result of researches and investigations, the 800 kW wind turbine was designed and simulated as parameters of blade which are, length R = 30m, maximum power coefficient C_{Pmax} = 0.44, tip speed ratio λ_{max} = 6.9.

As can be seen in Figure 6, the simulation has been started at initial value of v_{rated} = 10.3 m/s which is nominal wind speed and then wind speed was increased to 13 m/s. After a few seconds, it was decreased to 7 m/s from 13 m/s, then after a while it was increased to 10.3 m/s again.

The shaft speed is fixed by pitch control at wind speed larger than the nominal wind speed in Figure 7. In Figure 8, when the actual speed of turbine is lower than nominal wind speed, the power coefficient is fixed at C_P = 6.9 by the optimum torque control method and the power obtained from the turbine is only dependent on the wind speed, this means Maximum Power Point Tracking (MPPT) control is performed with optimum torque control.

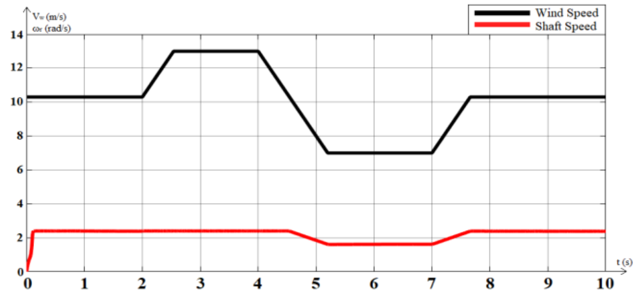

Figure 6. Wind speed and shaft speed.

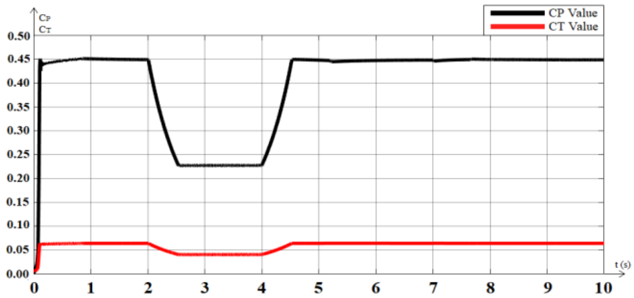

Figure 7. C_P and C_T values.

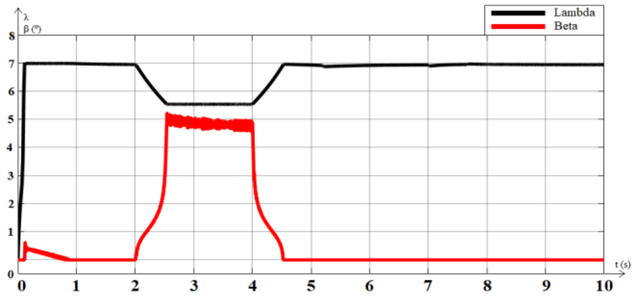

Figure 8. Tip speed ratio and pitch angle.

The graphic of the electromagnetic torque in generator is shown in Figure 9. In generator mod operate of machine, the electromagnetic torque is less than zero (0), for easy understanding in Figure 9, this value was multiplied with minus one (-1).

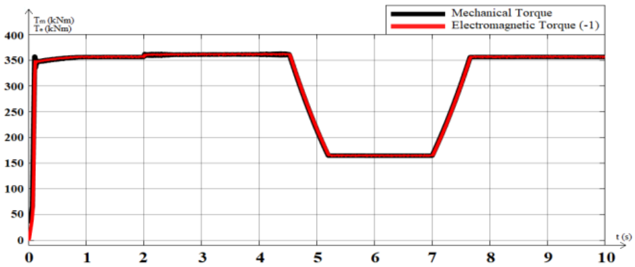

Figure 9. Mechanical torque and electromagnetic torque.

Figure 10 shows that the voltage of DC busbar is fixed at the reference voltage of 1200V. When the wind speed varies, DC voltage is a little bit fluctuated but as seen in Figure 11, the provided active power to grid is not fluctuated due to the charging/ discharging of capacitor.

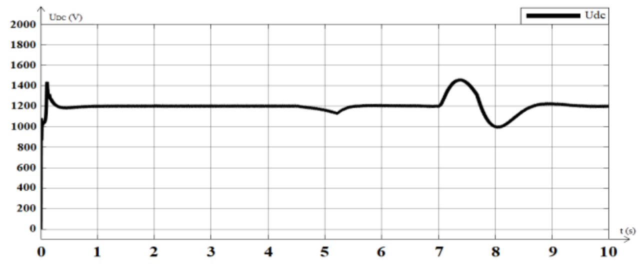

Figure 10. DC bus voltage.

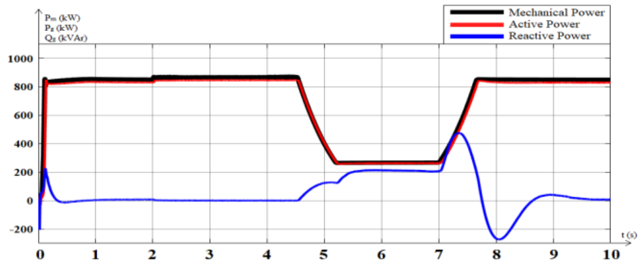

Figure 11. Mechanical power, provided active and reactive power to grid.

In Figure 12, three phase currents and dq currents of generator are given for first 0.5 second. Likewise, current and voltage of phase A belonging to converter and grid are given in Figure 13 and Figure 14 for first 0.5 second.

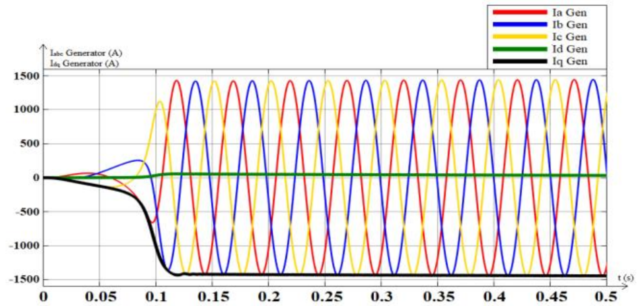

Figure 12. Generator three-phase currents and dq reference currents.

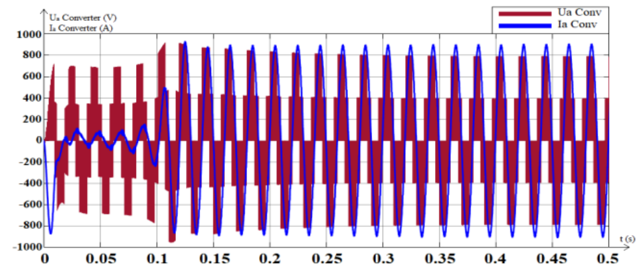

Figure 13. Phase-A current and voltage output of converter.

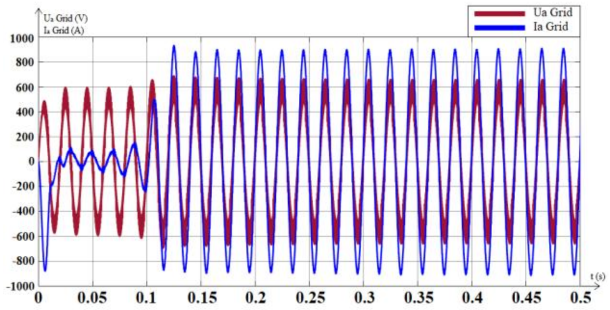

Figure 14. Phase-A provided current and voltage to grid.

As a result, the active power provided by turbine to grid is stable and the maximum power is obtained from the existing wind.

5. Conclusions

In this paper, the Variable-Speed Direct-Drive PMSG Wind Turbine connected to grid, was modeled as mathematical and controlled by converter. The voltages and the currents of the generator and grid was transformed to dq reference frame by park transforms. Thus, the equations of generator and grid were simplified. Simulation was performed at different wind speeds in order to show the system response. With method of optimum torque control, the shaft speed decelerated at low wind speed of rated wind speed. In this way the tip speed ratio was kept optimum, then turbine provided maximum power. The simulation results show that accuracy of the model, and applicability of the control system.

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Appendices

Table A.1. Parameters of PMSG.

Parameters	Symbol	Unit	Value
Rated Rotational Speed	n	rpm	18
Maximum Rotational Speed	n_{max}	rpm	21,6
Rated Electrical Frequency	f_n	Hz	15,6
Number of Phases	-	-	3
Connection Type	-	-	STAR
Rated Apparent Power	S_n	kVA	1036
Rated Load Voltage	V_n	V	591
RMS Phase Current (line)	I_n	A	1012
Open Circuit Voltage (line)	-	V	565
Inductance (phase)	L	mH	1,98
Resistance (ph/ph)	R	mΩ	13
Rated Power Factor	Cos (φ)	-	0,82
Rated Efficiency	η	-	0,94
Flux Linkage	Φ	Wb	3,123

Table A.2. Parameters of grid.

Parameters	Symbol	Unit	Value
Voltage (ph/ph)	V_{grid}	V	690
Frequency	F_{grid}	Hz	50
Inductance	L_{grid}	mH	0,3466
Resistance	R_{grid}	Ω	0,0662
Filter Inductance	L_{filter}	mH	1,1

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