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Development of a 10kW PEM Fuel Cell System Equipped with Polymer Composite Bipolar Plates

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***Abstract*—Among the midterm actions of "National Strategy of Iran Fuel Cell Technology Development", is designing and constructing polymer fuel cell system with the power of 10kW. However, this measure was performed before the commencement of this period. The 10kWfuel cell system was included two 65 cells stack equipped with 260 composite bipolar plates. This article presents, in separate chapters, the steps of designing, manufacturing and testing the bipolar plates, stack and the system of a 10kWPEMFC in Materials and Energy Institute of Isfahan. The advantages of this sample will be investigated in comparison with the first system made in this Institute with the capacity of 5kWfinally.**

***Index Terms*—Bipolar, Controller, PEM Fuel Cell, Stack**

I. INTRODUCTION

Mastering the design and integration of Proton Exchange Membrane Fuel Cell (PEMFC) systems and manufacturing its prototype, are among the important parts of short term measures of "National Strategy of Iran Fuel Cell Technology Development". In order to achieve this goal, the research project of designing and constructing 5kW Proton exchange membrane fuel cell(polymer electrolyte membrane) was defined with the aim of developing technical knowledge in Renewable Energy Organization of Iran. In 2010, the first generating heat and power simultaneously system with the basis of 5Kw fuel cell was manufactured by the researchers of Materials and Energy Institute of Isfahan. This system was installed at the site of Taleghan Renewable Energy Park, under the supervision of experts in Renewable Energy Organization of Iran [1].

Following the project of designing and manufacturing the 5kW fuel cell system, in 2010 the manufacturing of a 10kW collection was handed over to this institute again. Some of the goals the achievement of which was considered after performing this project include: dominance on design technology, constructing and testing polymer electrolyte membrane stack with higher capacity, an increase in the percentage of domestic manufacturing, increasing efficiency, decreasing the capacity and weight, decreasing the expenses and simplifying the system usage. In 2012, designing and manufacturing a sample of 10kW was conducted by considering the goals mentioned above. Moreover, the sample under investigation was installed in the site of Renewable Energy Organization at Taleghan.

Designing and manufacturing polymer electrolyte membrane fuel cell system with the power of 10kW was one of the important parts of Midterm actions of National Strategy of Iran Fuel Cell Technology Development. This measure was performed at the end of the first 5-year plan (short term actions), and before the commencement of the medium term period [2]. Meanwhile, dominance on 5KW stack technology and bipolar plates which were among the short term goals of document action plan, were performed in this project. Therefore, in addition to the accomplishment of the measures related to PEM fuel cell in the first period of 5 years, the important step which was presented in the second period of 5 years was also taken with success.

II. MANUFACTURING OF COMPOSITE BIPOLAR PLATES

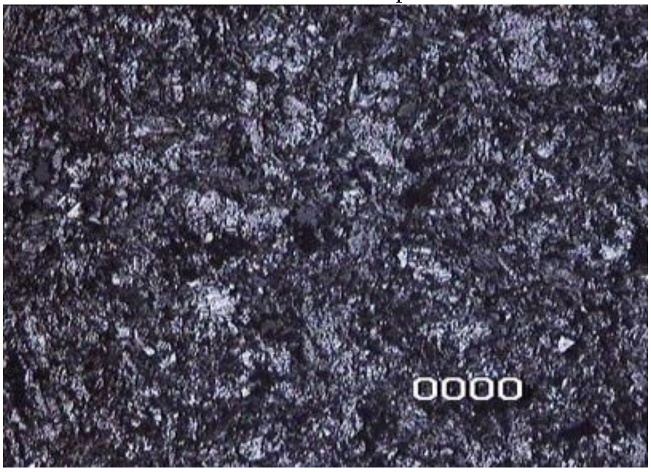
Bipolar plates must distribute the two gases of hydrogen and oxygen uniformly in the active area of cells. Also they should be able to conduct heat and power from one unit to another. According to the fact that hydrogen and oxygen are used in these fuel cells for generating power, these plates must be able to prevent gas leakage into the outside environment. Moreover, they must prevent combination of the two gases of hydrogen and oxygen. Bipolar plates, also, can have an effective contribution in decreasing volume, weight and expenses of a PEMFC stack. Thus, determining an appropriate material for the bipolar plates can have a significant effect in the output and final cost of fuel cells. According to the appropriate properties of polymer bipolar plates (table 1), in many applications polymeric composites have become conventional in comparison with steel and graphite plates due to lack of corrosion and good strength.

Table1. Desirable properties of bipolar plates

Properties	Unit	Polymeric Composite
(Through-plane) Electric Conductivity	s/cm	>100
(in-plane) Electric Conductivity	s/cm	>50
H2 permeability	cm3/(cm2s)	<2x10-6
Flexural Strength	MPa	35
Compressive Strength	MPa	70
Density	gr/cm3	<2
Cost	$/KW	<150

Polymeric composites are divided into two groups of thermo set [3]-[5] and thermoplastic [3], [4]. The usage of thermo set composites is more common in fuel cells due to the operating temperature of cells and the tendency towards high temperature cells. Among thermo set resins, epoxy has been the first option which was chosen in manufacturing plates, due to excellent mechanical properties and high chemical resistance [3]. Accordingly, in this research, epoxy resin was selected by low viscosity (for improving the mixture). Therefore, the epoxy resin of EPON828 type, which is produced by Shell Co and is popular in the market, was used. First, epoxy, graphite and carbon black are mixed with each other. The hardener type should be chosen as high-temperature for the resin. The hardener was selected as Diaminodiphenylsulfone. After molding, some measures were conducted by mechanical and electrical tests and microscopic images in order to improve the properties of the samples. . In figure 1, a picture of typical particle distribution in the sample is shown. The uniformity of the distribution and lack of Holes existence have been effective in improving the stages of mixture and curing.

Fig. 1: Distribution of graphite particles and resin in a sample



After optimization, the best condition of curing and composition percentage of composite components determined at 220 ° C and 270 barg.

Much time taking for curing composite, is one of the problems which exist for manufacturing plates on the basis of epoxy. Therefore, despite the use of epoxy in early samples, vinyl ester resin was used in stack production of plates in order to increase the speed of curing. However, the physical and chemical properties of vinyl ester are so similar to epoxy.

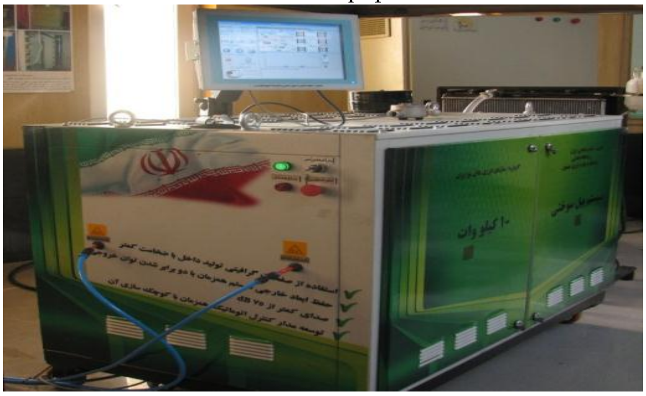
III. Introducing 10kW Fuel Cell System

One type of fuel cells which are used in building centralized power plants and distributed generation systems are polymer electrolyte membrane fuel cells (PEMFC) [1].

Electrolytes which are used in 10kW fuel cell system are of polymeric type. Moreover, the application of this system is a distributed generation (DG). This system has two polymeric stacks constituting of 65 cells each. The net power of this system is 10kW and the pick power is 14 kW (Figure 2). According to its accessorial equipment, this system has six separate circuits which include:

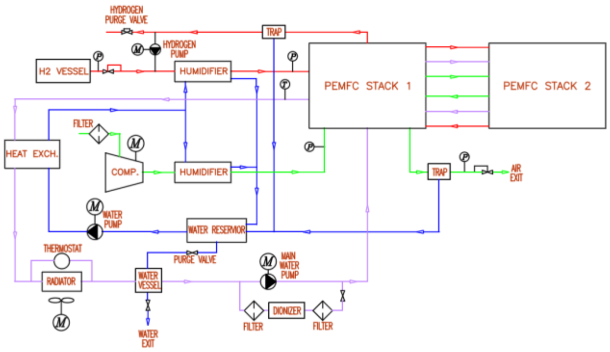
- ✓ Fuel management system
- ✓ Oxidant management system
- ✓ Cooling system
- ✓ Control and monitoring system
- ✓ Safety system and leakage control
- ✓ Energy conversion system

Fig 2: 10kW fuel cell system package included all accessorial equipment



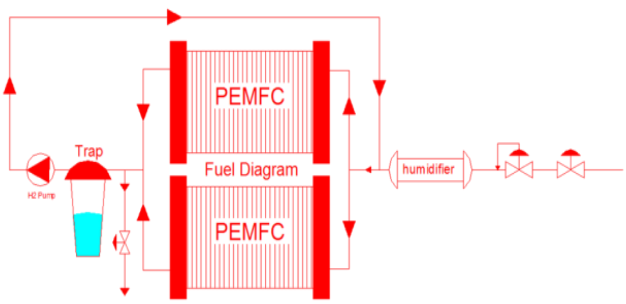
The schematic illustration of fuel circuits, oxidant and cooling fluid have been shown as a complex in figure 3.

Fig. 3: Complex sub systems circuit, supplying oxidant, fuel and cooling Fluid



The fuel circuit and oxidant circuit are supposed to deliver hydrogen and oxygen to the stacks 1 and 2, in controlled pressure, temperature, humidity and fluidity [6]. Supplying system of hydrogen includes hydrogen storage, hydrogen input solenoid valve to the system, humidifier, pressure sensor, temperature sensor, water trap, hydrogen pump and discharge valve or hydrogen purge. Designation and selection of these equipments are made so that the pressure difference between anode and cathode does not exceed 0.2barg, in system's working pressure which is adjusted between 0.1 barg and 0.5 barg. Stoichiometric coefficient of oxygen and stoichiometric coefficient of hydrogen are 2.5 and 1.5, respectively. Moreover, oxygen outlet and hydrogen outlet are respectively flow through and dead end with alternate purges. Figure 4, shows the schematic image of fuel circuit.

Fig. 4: The schematic image of fuel circuit

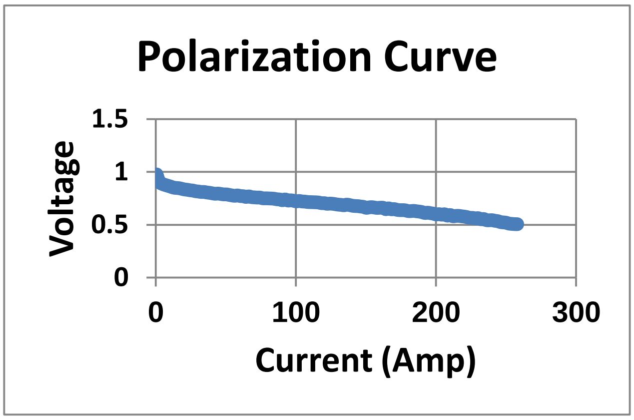


The oxidant circuit of this system is almost similar to its fuel circuit. However, they differ in that the required oxygen is supplied by a compressor which works with dc power and is humidified before entering into the stack. Moreover, the humidifier of hydrogen has been removed in the final test of the system. The humidifier of hydrogen was removed because there was enough humid due to the reaction on the side of anode which was because of the large number of cells.

IV. Stages of Testing the 10kW Fuel Cell System

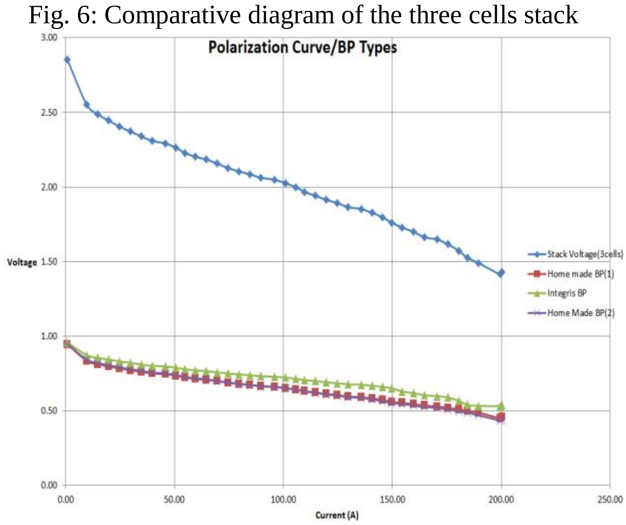
Before manufacturing of 65 cells stack which belonged to the 10kW fuel cell system, one mono cell and a 3 cells stack were manufactured and tested. By testing the mono cell, investigating the function of membrane electrolyte assembly (MEA) for manufacturing the 10kW fuel cell system was aimed. Figure 5 shows the polarization diagram (V-I) of this single cell.

Fig. 5: Polarization diagram (V-I) of the PEMFC single



The purpose of manufacturing the three cells stack was to compare the quality of polymer bipolar plates which were produced in Materials and Energy Institute of Isfahan and the similar ones which were made in other companies. All membranes are the same in this stack. However, the bipolar plates of the first cell were foreign ones while the plates of the second and third cells were homemade productions. The comparative diagram of three cells stack is presented in figure 6.

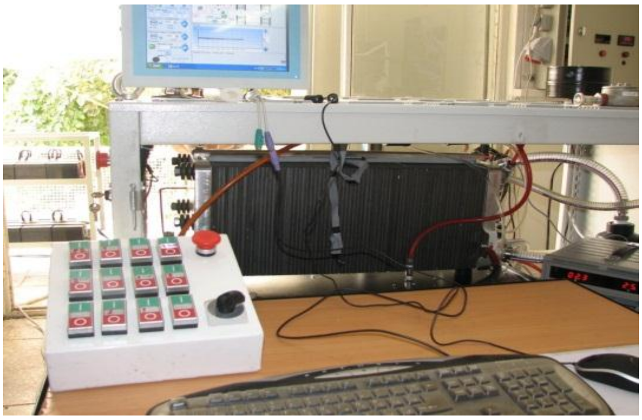
Fig. 6: Comparative diagram of the three cells stack



As it is shown in the above diagram, performance of the two prototype samples of homemade production plates and the foreign ones, were so close. After confirming the bipolar samples, producing 130 cells of two 65 cells stacks, which were the main section of the 10Kw fuel cell system, were assembled. Then the stages of stack leakage and voltage stability test and MEA break-in test were all performed separately, on each of these two stacks. Then, the two stacks were installed within the system.

The 10kW fuel cell system was tested several times with different loads. In each of these tests the voltage stability was investigated in accordance to constant current, gas flow rate, air compressor speed, hydrogen pump speed, and gas pressure difference between anode and cathode side, cells temperature, and flooding level. The simultaneous test of the two stacks which are connected to each other in series condition is shown in figure 7.

Fig. 7: The 10kW fuel cell system under the test



After adjusting the parameters mentioned earlier, the algorithm of the cell's auto control software was provided and uploaded in the system. Later, the system was tested several times in regard of power production level andits stability. Figures 8 and 9 present the diagram of voltage-time (sec) and the diagram of power and voltage-current, relevant to one of these tests.

Fig. 8: The diagram of voltage-time (Sec), relevant to one of the system's stability tests

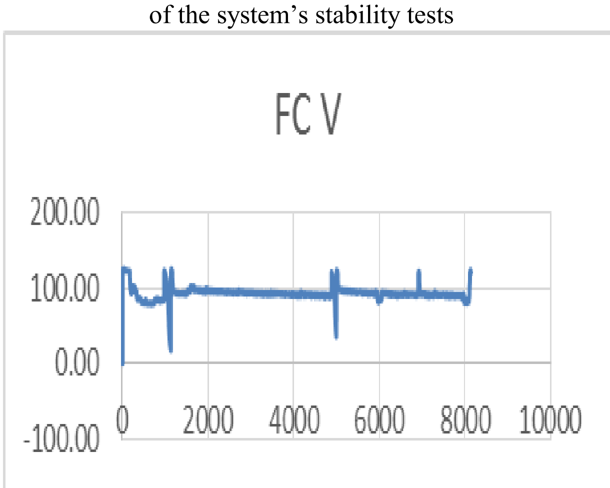
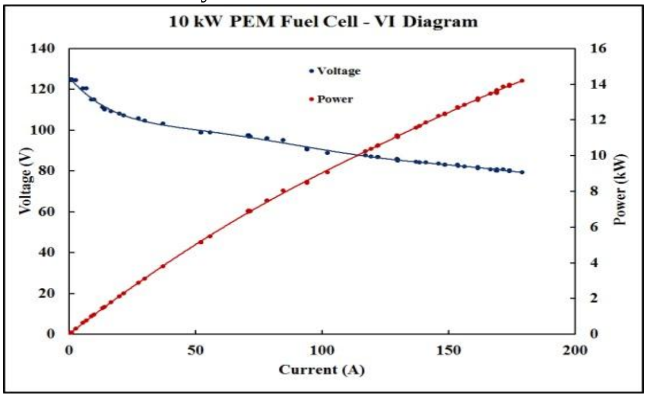


Fig. 9: The polarization and power diagram of the 10kW system in one of the tests



V. Fuel Cell Control System

The control system of fuel cell is divided into the following cases, based on the six subsystems referred to earlier, in section 4:

- ✓ The controller of hydrogen supply system
- ✓ The controller of oxygen supply system
- ✓ The controller of stack's cooling equipment
- ✓ Safety and security system
- ✓ Main system controller
- ✓ Fuel cell energy conversion system

In the following, it is proposed a general introduction to each of the above circuits and equipment [9].

The Controller of Hydrogen Supply System

The equipment which requires to be controlled is discussed in this part:

A. Hydrogen pump

The gas flow rate required by the stack is controlled by pump control through the analog input of 0-5 Vdc. Voltage supply provides the controller's supply for the motor as it is proportional to the voltage. Therefore, the motor's speed would become proportionate to the control signal. The control system is supposed to send the analog command and to receive the motor controller's feedback and finally to send the feedback to the system's main controller.

B. Input valve and hydrogen purge valve

The command to open these solenoid valves is sent by the control system to the relevant relay. The relay, then, provides the supply required for the valve to open.

C. Pressure sensors

Another task of the control circuit of the fuel supply equipment is to equalize the pressure on both sides of the membrane. Continuously reading the pressure degree on both sides by pressure sensors embedded in the system, one can make particular control decisions for obtaining the desired pressure.

D. Temperature sensors

In order to provide good working conditions for the fuel cell system, the temperature of hydrogen and oxygen and also the temperature of the cooling water, are measured by temperature sensors and then are given to the system controller.

A. The controller of air supply system

The major components of air supply system which are in relation with the control system include the compressor, humidifier, temperature sensor and pressure sensor. Next, each of these components is discussed separately.

A. Compressor

The supply required by the controller must be provided first in order to run the compressor. The compressor's operating point is determined by speed request signal which is a 0-5 volt signal. This signal is sent to the compressor through an analog output module.

B. Temperature sensor and pressure sensor

Task of the temperature sensor and pressure sensor in the air control system is similar to the role of this equipment in the fuel supply system.

B. The controller of stack's cooling equipment

In order to cool the radiator related to the cycle of the cooling water in the fuel cell, two fans of 24 volt were used. The radiator's cooling fan is controlled by one separate board. One micro-controller is embedded in this module which sends the square wave, with certain produced pulses, into the IC TLP250 and the IC output goes to the MOSFET's gate. The MOSFET switches on and off the fan's power. One can set the temperature of the output water to the desired level, by turning the MOSFET on and off through certain task cycle and also by using control algorithms.

C. Safety and security system

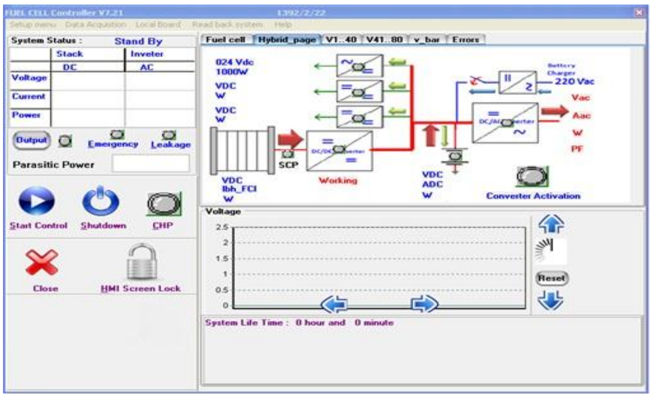
According to the NFPA standard, the fuel cell system must be equipped with the hydrogen gas detector. The detectors should be installed under the room's ceiling and up a place where is more likely to hydrogen leakage. Gas detection system must show warning in 25 percent of the LEL level (lower explosive limit) and must automatically turn the fuel cell system off in 60 percent of the LEL level. In addition, a portable gas detector will be embedded within the fuel cell system for detecting minor leaks of hydrogen [7].

D. Main system controller

The main system controller is supposed to control the system based on predetermined algorithms. The controller performs this act through actuators such as pumps, solenoid valves and also through receiving sensors data.The controller can be either analog or digital. Moreover, it can be implemented by computer and numerical processors; this way, the controller is connected to the process by A/D and D/A converters.

The control system is designed in such a way that the overall configuration of the system is determined after investigating the electrical characteristics of the control system components, through investigating its type and its components' signals. Then, the component's signals will be classified and suitable control circuits will be specified to them, based on the type and number of the analog and digital signals. The system's processor must have high flexibility. Therefore, the touch panel industrial processors were in priority to be chosen. Figure 10 shows the software of 10kW fuel cell control system.

Fig. 10:10kW fuel cell control system software

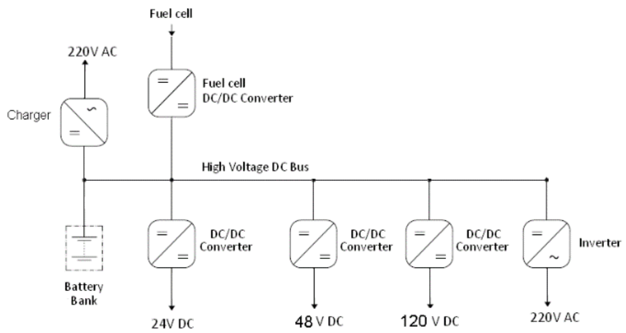


E. Fuel cell energy conversion system

The output voltage range of a fuel cell in a system of 10kW is about 65 to 150 Volts. This voltage range, however, is not in accordance with the voltage characteristics of the existing equipment in the system. Therefore, one should use converter for supplying the auxiliary unit power.

Voltages of 24 and 120 volts are applicable for most pumps and motors and electrical circuits. For this purpose, several internal converters are also required in order to change the voltage of fuel cell to a desired range. On one hand, rapid changes of load demand flow in the output of fuel cell system is another problem which can lead to damage in the fuel cell. Batteries are used in order to reduce the effect of such shocks to the fuel cell. In other words, a battery causes the reduction of load fluctuations on the fuel cell by supplying energy when needed. In figure 11, the schematic circuit of the hybrid system is presented [10].

Fig. 11: Schematic of fuel cell energy conversion system



As it is shown in this circuit, the fuel cell output is delivered to the high voltage bus by a dc/dc converter. The output voltage of the hybrid system is 220V, 50 Hz ac. This voltage is made by a dc-ac inverter, converting dc to ac, from the constant voltage existing in the high voltage bus. The power required by the components of fuel cell system is provided from high voltage bus, by converters presented in the figure 11. In this composition, a battery was used for the initial start-up of the system and for presenting additional power of load demand and also for preventing from the entrance of current shock to the fuel cell [8].

VI. Conclusion

In order to develop the use of decentralized small units of fuel cell in Iran, and after the successful production of a 5kW fuel cell system with a basis of polymeric electrolyte in Materials and Energy Institute of Isfahan, a 10kW fuel cell system was designed, constructed and successfully tested with the possibility of simultaneous use of heat and power. This system is equipped with two stacks of 65 cells which produce 180 amps current in working voltage of 78 volts. The output voltage of this system has been changed to a single phase ac and voltage by a series of ac/dc converters and dc/ac inverters. In order to make this hybrid 10kWsystem, a battery was used for the initial start-up of the system, requesting additional power load and for preventing from the entrance of current shock to the fuel cell. The output of this 10kW system is 220 volts AC power and 14 kW heat.

The superiorities of the 10kWsystem compared with the 5kWsystem are presented below:

- Reducing the total cost and the time

The 10kW system was constructed with an equal expense of the initial 5KW system; however, the capacity, material and equipment used in the 10kW system were approximately twice as those of the 5kW system. Moreover, despite of producing bipolar plates, the performance time of the project was reduced to two years in the 10KW system while this performance time was three years in the sample of 5KW.

- Increasing the percentage of local manufacturing of fuel cell components, while reducing of its cost and time.

During constructing of 10kW system, mass production of polymer bipolar plates in desired sizes and dimensions became possible within the country. This possibility took place due to designing and manufacturing molds for polymer bipolar plates in industrial dimensions and successful use of them in 10kW fuel cell stacks. The cost and time of manufacturing of fuel cell stacks have greatly reduced by the possibility of manufacturing these plates in both blank and grooved forms.

Now, polymeric composite plates have the most applications in PEM fuel cells, according to their acceptable conduct, low cost and high strength. Therefore, an extensive study has been carried out regarding of their characteristics and properties of composite plates and their manufacturing process in two types of thermoplastic and thermo set.

By designing and manufacturing of plate molds of fuel cells in industrial dimensions, the possibility of mass production of these plates (less than 10 minutes time for producing of each plate) and application of these samples in PEM fuel cell stacks, were achieved.

Local manufactured of thermo set plates, have good quality according to the existing standards for being applied in fuel cells.Even, in some characteristics these local plates functioned better compared with the foreign samples. For instance, a mono cell equipped with local production plates, in 0.6 volt, was capable of producing 225 amps current, for 225 square centimeters active area. However, this number, in similar conditions and with foreign plates with the same dimensions was 200 amps. Moreover, local production plates are comparative with the foreign samples in regards of mechanical strength and weight reduction especially in cells with higher powers.

- Increasing the efficiency of electrical converter

In comparative with the 5kW system, the 10kW converter was optimized and its total efficiency was increased up to 85%.

- Reducing pressure and noise of the system

In case the fuel cell system works in lower pressure, the possibility of stack leak becomes less and it will be much easier to control the leakage and also the depreciation of the system becomes less. The maximum pressure of 5kWsystem was considered to be 0.7 barg on the anode side and 0.6 barg on the cathode side. However, according to the advantages of system performance in lower pressures, the compressor and other equipment in this project such as hydrogen pump were chosen in such a way that the air pressure do not exceed 0.3 barg on the cathode side, while maintaining the optimal performance of the system. Furthermore, there was an attempt to use a compressor which makes the minimal noise.
In 5kW fuel cell system, two hydrogen pumps were used. Meanwhile, the noise of these pumps reached to 85 db and led to an increase in the overall noise of the system. In 10kW system only one pump was applied instead of the two for each two fuel cell stacks. This fact can cause to save the consumption of 200 watts of power consumption. Moreover, the noise pollution level of this hydrogen pump equals 70 db and thus by using this pump the overall noise of the system was greatly decreased besides increasing in its efficiency.
In addition to the above mentioned points, the following issues are also considered among the notable advantages of the 10kWfuel cell system in comparison with the 5kWfuel cell system:

✓ The acquisition of production of higher technology stacks Output net power of system is doubled in 10kWsystem with the same external dimensions in 5kWsystem.

✓ The possibility to produce power and heat simultaneously, for an official or residential environment with an area of 100 square meters

✓ The development of control and monitoring software and the capability of automated control

✓ Setting up a digital converter

✓ The development of automatic control circuit and simultaneously downsizing

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