MATLAB/Simulink Modelling of PEM Fuel Cell and Reactant Flow Pressure Control Schemes for Performance Evaluation

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***Abstract*—** Fuel cells have proven to have the potential to re-establish how things are powered on our planet, from small- to large-scale. They are a gateway to clean, reliable, and optimal energy generation. Studies and their applications have showed that they diminish usage of polluting fuels significantly, in turn helping the world shift from traditional fossil fuels to cleaner alternatives. Pressure control of reactants in fuel cells is an ongoing research. Mathematical modeling of Proton Exchange Membrane Fuel cell (PEMFC) using MATLAB/Simulink is carried out in this study for investigating the performance of PEMFC with the static and dynamic load. The mechanism for controlling reactant pressure within the fuel cell is a simple PI controller. The behaviour of PEMFC with PI controller in static and dynamic DC loading conditions is illustrated. The study concludes that simple PI controller works well with in these conditions.

***Keywords*—Fuel Cell, PEMFC, PI Controller, Static Load, Dynamic DC Load**

I. INTRODUCTION

Fossil fuels and their subsidies are very mainstream even in 2021, and have been polluting our planet since industrialization. Growth in renewable energy (RE) sector has picked up in recent times, especially since 2011. In 2020, installed power capacity of RE sector grew by approximately 256 gigawatts (GW). Around 29% of electricity in the world comes from renewable sources, and this is projected to keep growing.[1] One such up and coming important technology is fuel cell technology.

Compared to traditional combustion engines, working of a fuel cell is relatively cleaner and more efficient. They directly convert the fuel's chemical energy into electricity, and this is subsequently used to run various electrified systems. As the intermediate thermo-mechanical steps in conventional energy converters (heat engines) or combustion are not required, fuel cell conversion is way more efficient.

One of the most important advantage of fuel cell technology is that the process which is used can regenerate hydrogen. This reduces both pollutant and climate-damaging gas emissions. Hence fuel cells can play an important part in decarbonizing propulsion as well as energy systems. The fuel cell generates energy through an electrochemical reaction; oxygen and hydrogen combine to form electricity, heat and water. Application of fuel cells range from e vehicles to critical and sensitive infrastructure. All over, fuel cells are green, clean, highly efficient and reliable forms of power generation.

Inside the fuel cell, protons travel through a porous membrane of electrolytes, whereas electrons go through a circuit; these processes lead to generation of heat and electric current. Electrons, protons, combine at cathode with oxygen, which produces water. The process functions with an extremely high degree of reliability. Since there is no wear and tear, the operation is silent because of absence of moving particles.

Fuel cells on pure hydrogen are completely carbon-free, and their only by-products are electricity, heat, and water. Some fuel cell also use hydrocarbon fuels such as natural gas, biogas, and methanol to produce hydrogen. Waste heat of fuel cells can be used to drive thermal systems and cooling applications.

Fuel cells are scalable, that is, the individual fuel cells can be joined in a stack. Constrains in fuel cell development include the choice of electrolyte. The main electrolyte types are mentioned in the next section. Some use liquid while some use solid electrolytes.

Some types of fuel cells require pure hydrogen, and reformation reaction is incorporated as a part of the system. Fuel cells can also tolerate some impurities, but sometimes may require higher temperatures to run efficiently. Circulation of liquid electrolytes is done using pumping operation. Solid electrolyte need higher operation temperatures than liquid electrolytes.

Every type of fuel cells has its unique merits and limitations. Fuel cell technology is still in its pilot/lab phase, and not yet cheap or efficient enough to widely replace traditional power generating methods.

II. LITERATURE REVIEW

A commercialized PEMFC performance parameters are discussed in [2]. The short board effect makes the evaluation of flow distribution of the stack important for the aspect of energy conversion of the series arrangement. The method is a combines a model derived with computational fluid dynamics (CFD) on one hand and an empirical model on the other. It considers air flow distribution. The air flow distribution in turn is predicted by the said CFD-based model. The performance of the empirical model is evaluated experimentally.Ultimately, the impact of configuration of PEMFC stack, configuration, number of cells, and current density of cells are seen on flow distribution and performance of PEMFC. The study concludes that U-type configuration promotes more uniform voltage than Z-type. Voltage increases with increase in number of cells .

[3] creates an observer based controller operating in sliding mode for PEMFC. The inputs are flow rate of hydrogen fuel and that of cooling air. There are also two outputs-output voltage and temperature of the stack. The PEMFC model is nonlinear and transient in nature.It is verified experimentally. A cooling fan controls the fuel cell operating temperature. A hybrid control structure is developed with the two and compared against the traditional proportional integral controller. The proposed controller in this study outperforms the conventional PI controller in terms of checking disturbances and tracking the maximum power tracking point.

[4] determines how effective the direct liquid water injection scheme and inter-digitated flow field design is in providing adequate gas humidification to maintain membrane hydration and reduce the mass transport limitations of the reactants and electrode flow. This study concludes that direct liquid water injection integrated with the inter-digitated flow fields is an optimal water management scheme resulting in higher transport rates of reactant and products, increased hydration state and conductivity of the membrane and increased cell tolerance limits in case of surplus injected liquid water. This can even fulfil the purpose of simultaneous evaporative cooling.

In [5] a fuzzy controller is used for vehicles powered by hybrid systems The proposed scheme stabilized voltage on DC bus by setting reference values with a control loop. A fuel cell/battery hybrid power system is developed on Simulink MATLAB for this study. It concludes that bat-fuzzy-FO-ASTSMC consumes minimum hydrogen compared to state machine while improving the fuel cell efficiency and decreasing fluctuation.

In [6] reactive energy consumption is decreased by using inverters lessening harmonic distortion.

[7] proposes a wide input range dc-dc converter to go with a robust power control scheme. This has two stages: a three-level boost converter stage followed by a current-fed two-inductor boost converter with higher voltage gain isolated from the input source. The front-end boost converter has the same voltage throughout. This is done to ensure optimal performance and high efficiency. Thus a constant output dc voltage for many load fluctuations is delivered.

In [8], a hybrid fuzzy PID controller is used for air supply in PRMFC to adjust O2 excess ratio to a desired set point. Components of this are: FLC, FSTPID, fuzzy selector. The error converted is difference of current value of O2 excess ratio and the set PT value. Based on error, fuzzy selector decides which controller will dominate the system. Load variations are implemented on a PGMFC model. The study concludes that hybrid fuzzy PID outperforms the regular PID controller. The comparison parameters used are ESE, IAE, ITAE, overshoot, settling and rise time.

[9], several power management strategies have been developed for FC hybrid vehicle systems. One is optimal control where fuel consumption is reduced and power drive is optimized based on Minimum Principle with and without state constraint. The study conclude that constant co-states can be used instead of variable ones for this scheme.

[10] is a study on hybrid FC power system. The components of this scheme are a unidirectional and bidirectional controller, inverter, and battery. Inclusion of battery enables cold start, improves system dynamic performance, provides peak power at overload condition, decreases power rating of cell, and reduces cost. A power management control scheme operates the bidirectional converter in boost, buck, or shutdown mode for changing and discharging of battery. All of this is simulated on a 1-kW lab FC model and the results of the experiment are depicted in the study.

In [11] a digital power control scheme, is proposed mainly a digital control strategy in front-end dc-dc converter of the fuel cell-battery hybrid power source for residential application. The polarization curve and efficiency curve of the fuel cell is drawn which shows that the fuel cell operates within the high efficiency region. This keeps the fuel cell operating within the high efficiency region. The fuel cell's access to is oxygen is also improved.

[12] There are control schemes applied to SOFC system with dynamic load. SOFC fuel cell with dynamic loading is modeled and behaviour is predicted. Then a control circuit model is applied to the dynamic model. Some control and manipulated variables are used. The study concludes that the schemes work well for SOFCs.

In [13] , a controller design using fractional PID, is developed for maximum power point tracking (MPPT). Lyapunov controller itself performs MPPT. Function also improves power quality. Through inverter, the principle is that the higher switching frequency is reduced by LCL filter. Thus, it is economic. It also improves power quality by reducing harmonic distortion in grid current utility grid through a single stage. It is feasible for power from PV and FC.

[14] uses a control scheme with Grey wolf optimizer (GWO) and PID controller for maximum power tracking in fuel cell. This is compared with P&O and INC, and PSO tuned PID performance in MPPT. Thus, dPdI feedback scheme based GWO tuned PID outperforms the other discussed techniques.

[15] suggests a control strategy to obtain food fuel and maintain cell conditions for a solid oxide fuel cell (SOFC). Cathode and anode reactants are represented as true bond graph models of an SOFC system.The utilization of fuel and air are measured.

III. METHODOLOGY

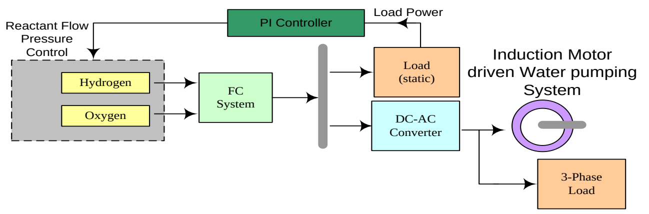

Fig. 1. Block diagram of proposed Fuel cell system and Power Management Scheme

Presented below is the mathematical model of PEMFC [Fig, 2] with varous input parameters, connected with a series RLC load, reference power and PI controller.

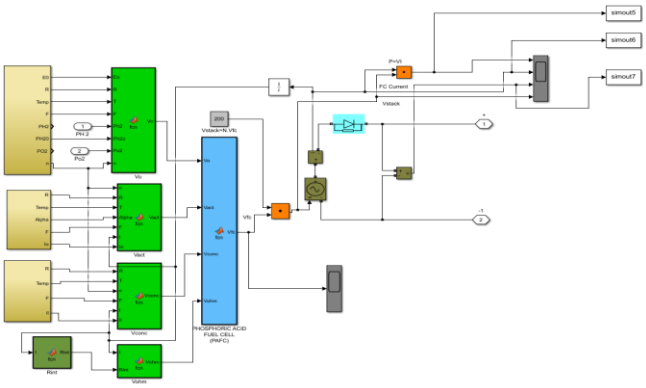

Fig.2 PEMFC Mathematical model

The pressure of oxygen and hydrogen calculation is done in functional blocks with the following equations:[17]

$$\text{Conc.O}_2 = \frac{\text{Po}_2}{5.08 \times 10^6 \times \exp^{(-498/T)}}.$$

Anode flow model equations

$$\frac{V_{\text{anode}}}{RT}\frac{\text{d}P_{\text{H}_2}}{\text{d}t} = m_{\text{H}_2-\text{in}} - m_{\text{H}_2-\text{out}} - \frac{I}{2F},$$

$$m_{\text{H}_2-\text{out}} = k_{\text{anode}}(P_{\text{H}_2} - P_{\text{amb}}),$$

$$m_{\text{H}_2-\text{in}} = \text{FR}_{\text{H}_2}\text{PF}_{\text{H}_2}\text{CF}_{\text{H}_2}.$$

Hydrogen flow pressure is calculated as,

$$\text{P}_{\text{H}_2} = \frac{m_{\text{H}_2}R_{\text{H}_2}}{V_{\text{anode}}}T.$$

Cathode flow model equations

$$\frac{V_{\text{cathode}}}{RT}\frac{\text{d}P_{\text{O}_2}}{\text{d}t} = m_{\text{O}_2-\text{in}} - m_{\text{O}_2-\text{out}} - \frac{I}{2F},$$

$$m_{\text{O}_2-\text{out}} = k_{\text{cathode}}(P_{\text{O}_2} - P_{\text{amb}}),$$

$$m_{\text{O}_2-\text{in}} = \text{FR}_{\text{O}_2}\text{PF}_{\text{O}_2}\text{CF}_{\text{O}_2}.$$

Oxygen flow pressure is calculated as,

$$P_{\text{O}_2} = \frac{m_{\text{O}_2}R_{\text{O}_2}}{V_{\text{cathode}}}T,$$

$$\frac{V_{\text{cathode}}}{RT}\frac{\text{d}P_{\text{H}_2\text{O}-\text{cathode}}}{\text{d}t} = m_{\text{H}_2\text{O}-\text{in}-\text{cathode}} - m_{\text{H}_2\text{O}-\text{out}-\text{cathode}} + \frac{I}{2F},$$

$$m_{\text{H}_2\text{O}-\text{out}-\text{cathode}} = k_c(P_{\text{H}_2\text{O}-\text{cathode}} - P_{\text{amb}}).$$

where,

E_0	reference Nernst potential (V)
R	universal gas constant ($\text{Jmol}^{-1}\text{K}^{-1}$)
F	Faraday constant (Cmol^{-1})
T	stack temperature (K)
P	FC pressure (atm.)
t_m	membrane thickness (cm)
C_{dl}	double layer capacitance (F)
D_{H^+}	diffusion coefficient (cmS^{-1})
P_{amb}	ambient pressure (atm.)
V_{anode}	anode volume (m^3)
V_{cathode}	cathode volume (m^3)
k_{anode}	anode flow constant ($\text{mols}^{-1}\text{atm}^{-1}$)
k_{cathode}	cathode flow constant ($\text{mols}^{-1}\text{atm}^{-1}$)
PF_{H_2}	H_2 purity factor
CF_{H_2}	H_2 flow rate conversion factor
CF_{O_2}	O_2 flow rate conversion factor
PF_{O_2}	O_2 purity factor
m_{in}	reactant inlet flow rate (mols^{-1})
m_{out}	reactant outlet flow rate (mols^{-1})
m_{H_2}	mass of hydrogen at the anode (kg/mol)
R_{H_2}	H_2 gas constant (J/kg K)
m_{O_2}	mass of oxygen at the cathode (kg/mol)
R_{O_2}	O_2 gas constant (J/kg K)
$m_{\text{H}_2\text{O}}$	mass of water at the cathode (kg/mol)
$q_{\text{H}_2\text{O}}$	molar flow rate of water (mols^{-1})
P_{H_2}	hydrogen flow pressure (atm.)
P_{O_2}	oxygen flow pressure (atm.)
$P_{\text{H}_2\text{O}}$	water flow pressure (atm.)

A MATLAB Model of the fuel cell is designed with a simple resistance for static loading[Fig 3]. The reactant pressure is varied in fuel cell stack with a PI-control scheme.
The dot product of the voltage & current measurement blocks produces power output of state loading.

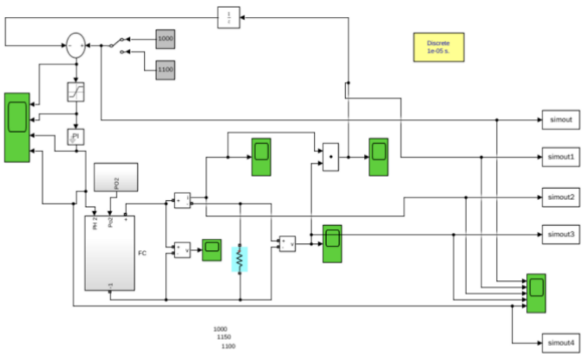

Fig.3 MATLAB model with static loading

Presented below is the mathematical model of PEMFC [Fig, 4] with various input parameters, connected with boost converter and in turn to dynamic DC load, reference power and PI controller. The load is made variable by using a MOSFET power switch. The first resistance is ON for 6 seconds and then for the next 6 seconds, both the resistances are ON. As a result, there is a sudden decrease in resistance after 6 seconds.

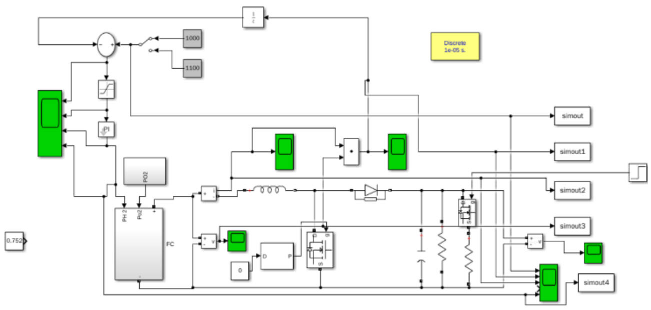

Fig 4. MATLAB model with dynamic DC loading

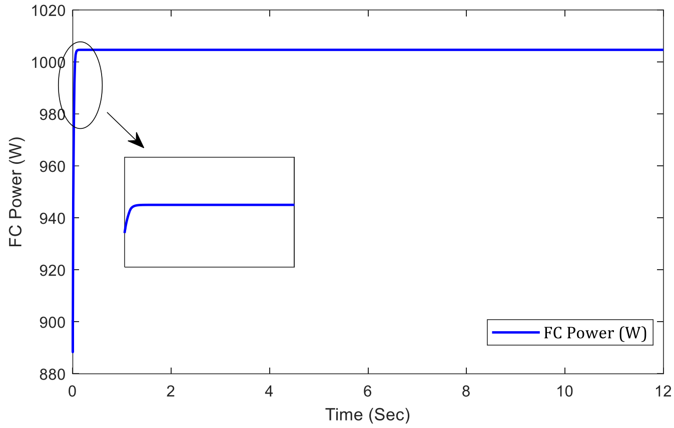

Fig.5. Fuel Cell Power Plot with static loading

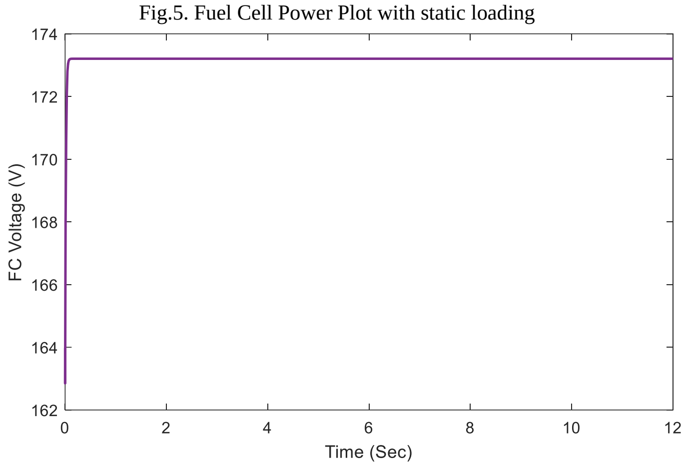

Fig.6. Fuel Cell Voltage Plot with static loading

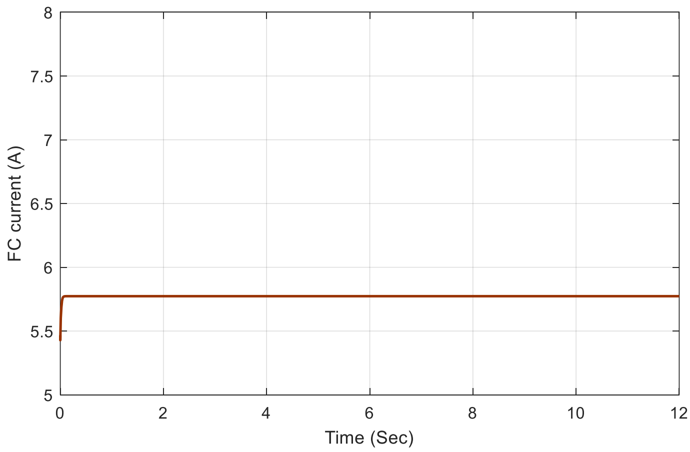

Fig.7. Fuel Cell Current Plot with static loading

IV. RESULTS

On simulating the MATLAB model with static loading [Fig. 3], the following is observed:

- The start-up time is significantly reduced and the Fuel Cell and the power is constant [Fig.5]
- Maximum voltage is maintained at 173 V [Fig.6]
- Maximum current is maintained at 5.7 A [Fig.7]

The MATLAB model with dynamic DC loading [Fig. 4], is simulated by varying resistance. The second resistance is twice the first. Power and voltage change accordingly after 6 seconds.
The initial slow rise is due to the start-up time of the PEMFC stack.

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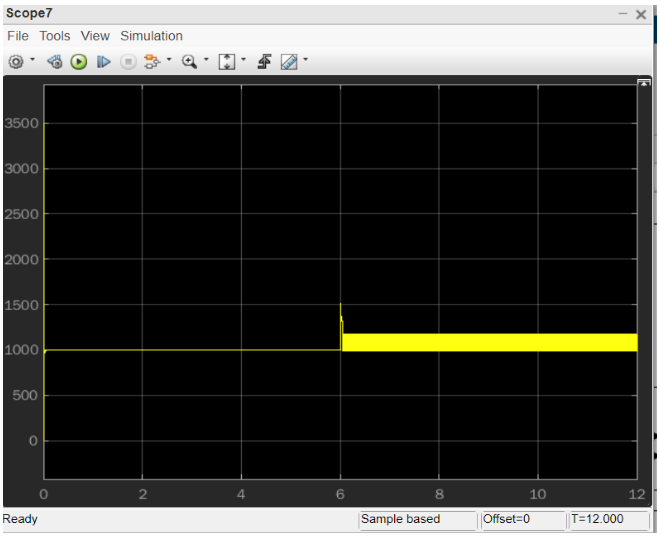

Fig.8. Power plot for change of resistance from 30 ohms to 60 ohms

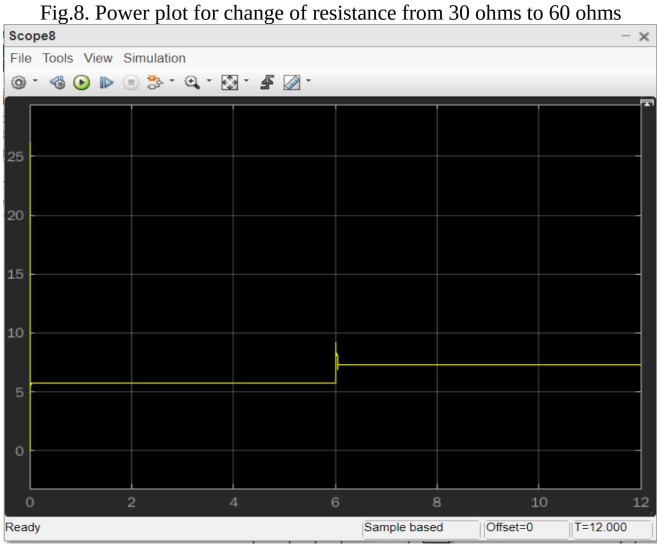

Fig.9. Voltage plot for change of resistance from 30 ohms to 60 ohms

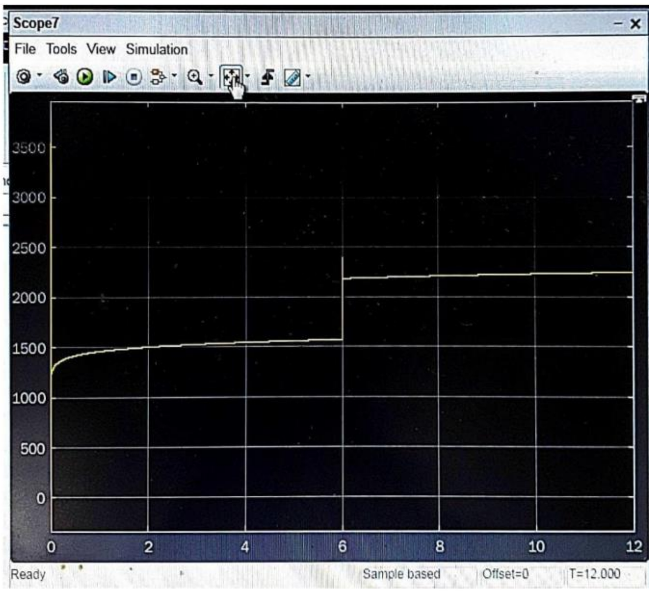

Fig.10. Power plot for change of resistance from 22 ohms to 44 ohms

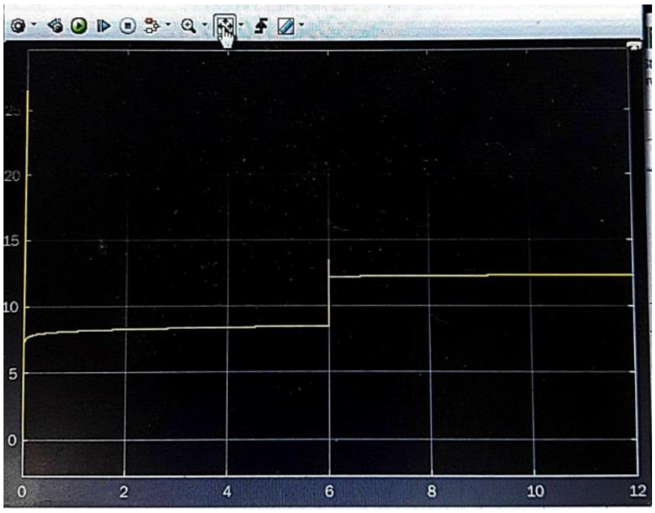

Fig.11. Voltage plot for change of resistance from 22 ohms to 44 ohms

V. DISCUSSION

The control scheme using a simple PI controller, when tested with simple static and dynamic DC loading shows favourable results. With static load, the PI controller manages to maintain a steady output.With dynamic loading, the system takes a while to readjust due to start-time of the PEMFC stack, but eventually reaches the desired outputs. When resistance is doubled, a steady state decrease in power and voltage is observed accordingly.

VI. CONCLUSION

PI-controllers are cost-effective and less complex alternative to control the flow of reactants in a fuel cell. The demonstration used simple DC loads — static and dynamic to interpret the behaviour and output of such a control scheme for a PEMFC. The behaviour and effect of this scheme for more complex fuel stacks and complex loads for applications in systems like e-vehicles is yet to be determined.

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