# NEURAL NETWORK CONTROL FOR PEM FUEL CELL

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# List of Acronyms

| | |
|---|---|
| **PEM** | Proton Exchange Membrane |
| **PI** | Proportional Integral |
| **NN** | Neural Network |
| **FC** | Fuel Cell |
| **V** | Voltage |
| **I** | Current |
| **ac** | Alternating Current |
| **dc** | Direct Current |
| **DC** | Distributed Generation |
| ***fig*** | Figure |
| **ANFIS** | Adaptive Neuro-Fuzzy Interface |

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# Abstract

This paper presents modeling, controller design, and simulation study of a proton exchange membrane fuel cell (PEMFC) distributed generation (DG) system. The overall configuration of the PEMFC DG system is given, dynamic models for the PEMFC power plant and its power electronic interfacing are briefly described, and controller design methodologies for the power conditioning units to control the power flow from the fuel cell power plant to the load are presented. A MATLAB/Simulink simulation model is developed for the PEMFC DG system by combining the individual component models and the controllers designed for the power conditioning units. Simulation results are given to show the overall system performance including load-following capability of the system.

# Chapter 1

# Introduction

## 1.1 Overview of fuel cell

## 1.2 Different types of fuel cells

### 1.2.1 Proton Electron Membrane Fuel Cells (PEMFCs)

### 1.2.2 Solid Acid Fuel Cells (SAFCs)

### 1.2.3 Alkaline Fuel Cells (AFCs)

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### 1.3.3 Portable Power Systems

## 1.4 Operation of proton exchange membrane (PEM) fuel cell

# 1.1

# OVERVIEW OF FUEL CELL

A fuel cell is an electrochemical device that converts the chemical energy of a fuel directly into electrical energy. The one-step (from chemical to electrical energy) nature of this process, in comparison to the multi-step (e.g. from chemical to thermal to mechanical to electrical energy) processes involved in combustion-based heat engines, offers several unique advantages. For instance, the current combustion-based energy generation technologies are very harmful to the environment and are predominantly contributing to many global concerns, such as climate change, ozone layer depletion, acidic rains, and thus, the consistent reduction in the vegetation cover. Furthermore, these technologies depend on the finite and dwindling world supplies of fossil fuels.

Fuel cells, on the other hand, provide an efficient and clean mechanism for energy conversion. Additionally, fuel cells are compatible with renewable sources and modern energy carriers (i.e., hydrogen) for sustainable development and energy security. As a result, they are regarded as the energy conversion devices of the future. The static nature of fuel cells also means quiet operation without noise or vibration, while their inherent modularity allows for simple construction and a diverse range of applications in portable, stationary, and transportation power generation. In short, fuel cells provide a cleaner, more efficient, and possibly the most flexible chemical-to-electrical energy conversion.

# 1.2

# DIFFERENT TYPES OF FUEL CELLS

There are many types of fuel cells available in the market today. Fuel cells are conventionally categorized according to their electrolyte material. They differ in their power outputs, operating temperatures, electrical efficiencies, and typical applications.

## 1.2.1 Proton Exchange Membrane Fuel Cells (PEMFCs)

**Proton Exchange Membrane Fuel Cells (PEMFCs)** have the largest range of applications as they are extremely flexible. PEMFCs are the most promising candidates for transport applications due to their high-power density, fast start-up time, high efficiency, low operating temperature, and easy and safe handling. However, PEMFCs are still too expensive to be competitive or economically-feasible.

## 1.2.2 Solid acid fuel cells (SAFCs)

**Solid acid fuel cells (SAFCs)** are characterized by the use of a solid acid material as the electrolyte. At low temperatures, solid acids have an ordered molecular structure like most salts. At warmer temperatures (between 140 and 150 degrees Celsius for $CsHSO_4$), some solid acids undergo a phase transition to become highly disordered "super protonic" structures, which increases conductivity by

several orders of magnitude. The first proof-of-concept SAFCs were developed in 2000 using cesium hydrogen sulfate ($CsHSO_4$). Current SAFC systems use cesium dihydrogen phosphate ($CsH_2PO_4$) and have demonstrated lifetimes in the thousands of hours.

## 1.2.3 Alkaline fuel cell (AFC)

The **alkaline fuel cell (AFC)** or hydrogen-oxygen fuel cell was designed and first demonstrated publicly by Francis Thomas Bacon in 1959. It was used as a primary source of electrical energy in the Apollo space program. The cell consists of two porous carbon electrodes impregnated with a suitable catalyst such as Pt, Ag, CoO, etc. The space between the two electrodes is filled with a concentrated solution of KOH or NaOH which serves as an electrolyte. $H_2$ gas and $O_2$ gas are bubbled into the electrolyte through the porous carbon electrodes. Thus, the overall reaction involves the combination of hydrogen gas and oxygen gas to form water. The cell runs continuously until the reactant's supply is exhausted. This type of cell operates efficiently in the temperature range 343 K to 413 K and provides a potential of about 0.9 V. AAEMFC is a type of AFC which employs a solid polymer electrolyte instead of aqueous potassium hydroxide (KOH) and it is superior to aqueous AFC. AFCs have the best performance when operating on pure hydrogen and oxygen, intolerance to impurities (especially carbon oxides) and short lifetimes hinder their role for terrestrial applications (they are predominantly used for extraterrestrial purposes).

## 1.2.4 Phosphoric acid fuel cells (PAFCs)

**Phosphoric acid fuel cells (PAFC)** were first designed and introduced in 1961 by G. V. Elmore and H. A. Tanner. In these cells phosphoric acid is used as a non-conductive electrolyte to pass positive hydrogen ions from the anode to the cathode. These cells commonly work in temperatures of 150 to 200 degrees Celsius. This high temperature will cause heat and energy loss if the heat is not removed and used properly. This heat can be used to produce steam for air conditioning systems or any other thermal energy consuming system. Using this heat in cogeneration can enhance the efficiency of phosphoric acid fuel cells from 40–50% to about 80%. Phosphoric acid, the electrolyte used in PAFCs, is a non-conductive liquid acid which forces electrons to travel from anode to cathode through an external electrical circuit. Since the hydrogen ion production rate on the anode is small, platinum is used as catalyst to increase this ionization rate. A key disadvantage of these cells is the use of an acidic electrolyte. This increases the corrosion or oxidation of components exposed to phosphoric acid. PAFCs are possibly the most commercially-developed fuel cells operating at intermediate temperatures. PAFCs are used for combined-heat-and-power (CHP) applications with high energy efficiencies.

## 1.2.5 Solid oxide fuel cells (SOFCs)

**Solid oxide fuel cells (SOFCs)** are high-temperature fuel cells appropriate for cogeneration and combined cycle systems. SOFCs use a solid material, most commonly a ceramic material called yttria-stabilized zirconia (YSZ), as the

electrolyte. Because SOFCs are made entirely of solid materials, they are not limited to the flat plane configuration of other types of fuel cells and are often designed as rolled tubes. They require high operating temperatures (800–1000 °C) and can be run on a variety of fuels including natural gas. SOFCs are unique since in those, negatively charged oxygen ions travel from the cathode (positive side of the fuel cell) to the anode (negative side of the fuel cell) instead of positively charged hydrogen ions travelling from the anode to the cathode, as is the case in all other types of fuel cells. Oxygen gas is fed through the cathode, where it absorbs electrons to create oxygen ions. The oxygen ions then travel through the electrolyte to react with hydrogen gas at the anode. The reaction at the anode produces electricity and water as by-products.

## 1.2.6 Molten carbonate fuel cells (MCFCs)

MCFCs require a high operating temperature, 650 °C (1,200 °F), similar to SOFCs. MCFCs use lithium potassium carbonate salt as an electrolyte, and this salt liquefies at high temperatures, allowing for the movement of charge within the cell – in this case, negative carbonate ions. Like SOFCs, MCFCs are capable of converting fossil fuel to a hydrogen-rich gas in the anode, eliminating the need to produce hydrogen externally. The reforming process creates $CO_2$ emissions. MCFC-compatible fuels include natural gas, biogas and gas produced from coal.

MCFCs hold several advantages over other fuel cell technologies, including their resistance to impurities. They are not prone to "carbon coking", which refers to carbon build-up on the anode that results in reduced performance by slowing down the internal fuel reforming process. Therefore, carbon-rich fuels like gases made from coal are compatible with the system. The Department of Energy

claims that coal, itself, might even be a fuel option in the future, assuming the system can be made resistant to impurities such as sulfur and particulates that result from converting coal into hydrogen. MCFCs also have relatively high efficiencies. They can reach a fuel-to-electricity efficiency of 50%, considerably higher than the 37–42% efficiency of a phosphoric acid fuel cell plant.

# 1.3

# APPLICATIONS OF FUEL CELL

## 1.3.1 Power

Stationary fuel cells are used for commercial, industrial and residential primary and backup power generation. Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks, communications centers, rural locations including research stations, and in certain military applications. A fuel cell system running on hydrogen can be compact and lightweight, and have no major moving parts. Because fuel cells have no moving parts and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability.

Since fuel cell electrolyser systems do not store fuel in themselves, but rather rely on external storage units, they can be successfully applied in large-scale energy storage, rural areas being one example. There are many different types of stationary fuel cells so efficiencies vary, but most are between 40% and 60%

energy efficient. However, when the fuel cell's waste heat is used to heat a building in a cogeneration system this efficiency can increase to 85%. This is significantly more efficient than traditional coal power plants, which are only about one third energy efficient. Assuming production at scale, fuel cells could save 20–40% on energy costs when used in cogeneration systems. Fuel cells are also much cleaner than traditional power generation; a fuel cell power plant using natural gas as a hydrogen source would create less than one ounce of pollution (other than $CO_2$) for every 1,000 kWh produced, compared to 25 pounds of pollutants generated by conventional combustion systems.

## 1.3.2 Cogeneration

Combined heat and power (CHP) fuel cell systems, including Micro combined heat and power (MicroCHP) systems are used to generate both electricity and heat for homes (see home fuel cell), office building and factories. The system generates constant electric power (selling excess power back to the grid when it is not consumed), and at the same time produces hot air and water from the waste heat. As the result CHP systems have the potential to save primary energy as they can make use of waste heat which is generally rejected by thermal energy conversion systems. A typical capacity range of home fuel cell is 1–3 $kW_{el}$ / 4–8 $kW_{th}$. CHP systems linked to absorption chillers use their waste heat for refrigeration.

The waste heat from fuel cells can be diverted during the summer directly into the ground providing further cooling while the waste heat during winter can be pumped directly into the building. The University of Minnesota owns the patent rights to this type of system.

Co-generation systems can reach 85% efficiency (40–60% electric + remainder as thermal). Phosphoric-acid fuel cells (PAFC) comprise the largest segment of existing CHP products worldwide and can provide combined efficiencies close to 90%. Molten Carbonate (MCFC) and Solid Oxide Fuel Cells (SOFC) are also used for combined heat and power generation and have electrical energy efficiencies around 60%. Disadvantages of co-generation systems include slow ramping up and down rates, high cost and short lifetime. Also, their need to have a hot water storage tank to smooth out the thermal heat production was a serious disadvantage in the domestic market place where space in domestic properties is at a great premium.

### 1.3.3 Portable Power Systems

Portable power systems that use fuel cells can be used in the leisure sector (i.e. RVs, cabins, marine), the industrial sector (i.e. power for remote locations including gas/oil wellsites, communication towers, security, weather stations), and in the military sector. SFC Energy is a German manufacturer of direct methanol fuel cells for a variety of portable power systems. Ensol Systems Inc. is an integrator of portable power systems, using the SFC Energy DMFC.

## Other applications include:

- Providing power for base stations or cell sites
- Distributed generation
- Breathalyzers, where the amount of voltage generated by a fuel cell is used to determine the concentration of fuel (alcohol) in the sample.

- Notebook computers for applications where AC charging may not be readily available.
- Food preservation achieved by exhausting the oxygen and automatically maintaining oxygen exhaustion in a shipping container, containing, for example, fresh fish.
- Carbon monoxide detector, electrochemical sensor.

# 1.4

# OPERATION OF PROTON EXCHANGE MEMBRANE (PEM) FUEL CELL

Polymer electrolyte membrane, also proton exchange membrane, fuel cells (PEMFC) are one of the most promising types already in the early commercialization stage. PEMFC's are being developed mainly for transport applications, as well as for stationary fuel-cell applications and portable fuel-cell applications. Their distinguishing features include lower temperature/pressure ranges (50 to 100 °C) and a special proton-conducting polymer electrolyte membrane. PEMFCs generate electricity and operate on the opposite principle to PEM electrolysis, which consumes electricity. They are a leading candidate to replace the aging alkaline fuel-cell technology, which was used in the Space Shuttle.

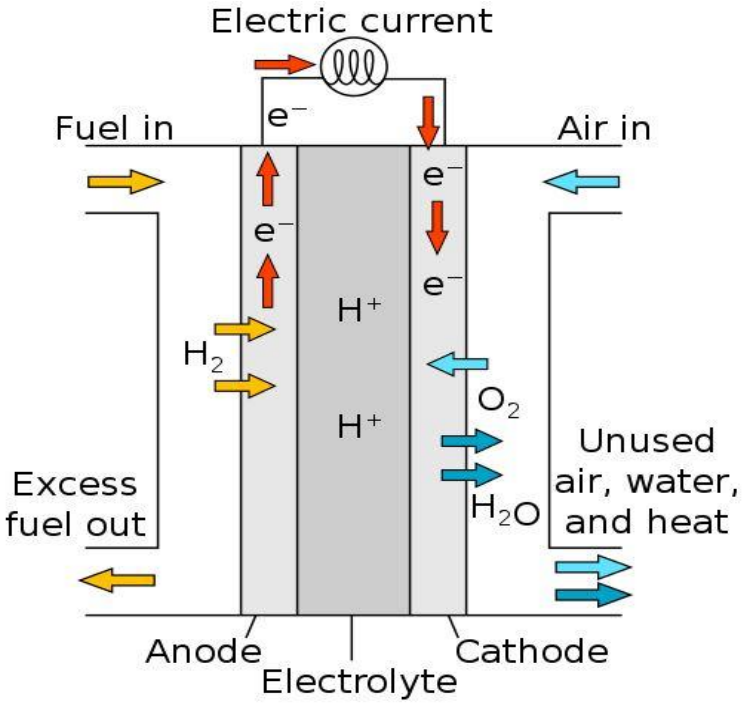



***Fig: 1.1*** *Diagram of a PEMFC*

PEMFCs are built out of membrane electrode assemblies (MEA) which include the electrodes, electrolyte, catalyst, and gas diffusion layers. An ink of catalyst, carbon, and electrode are sprayed or painted onto the solid electrolyte and carbon paper is hot pressed on either side to protect the inside of the cell and act as electrodes. The pivotal part of the cell is the triple phase boundary (TPB) where the electrolyte, catalyst, and reactants mix and thus where the cell reactions occur. Importantly, the membrane must not be electrically conductive so the half reactions do not mix. Operating temperatures above 100 °C are desired so the water byproduct becomes steam and water management becomes less critical in cell design.

A proton exchange membrane fuel cell transforms the chemical energy liberated during the electrochemical reaction of hydrogen and oxygen to electrical energy, as opposed to the direct combustion of hydrogen and oxygen gases to produce thermal energy.

A stream of hydrogen is delivered to the anode side of the MEA. At the anode side it is catalytically split into protons and electrons. This oxidation half-cell reaction or hydrogen oxidation reaction (HOR) is represented by:

**At the anode:**

$$\mathrm{H_2} \rightarrow 2\mathrm{H^+} + 2\mathrm{e^-}$$

The newly formed protons permeate through the polymer electrolyte membrane to the cathode side. The electrons travel along an external load circuit to the cathode side of the MEA, thus creating the current output of the fuel cell. Meanwhile, a stream of oxygen is delivered to the cathode side of the MEA. At the cathode side oxygen molecules react with the protons permeating through the polymer electrolyte membrane and the electrons arriving through the external circuit to form water molecules. This reduction half-cell reaction or oxygen reduction reaction (ORR) is represented by:

**At the cathode:**

$$\frac{1}{2}\mathrm{O_2} + 2\mathrm{H^+} + 2\mathrm{e^-} \rightarrow \mathrm{H_2O}$$

**Overall Reaction:**

$$\mathrm{H_2} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{H_2O}$$

The reaction is expressed in the equation and shows the reincorporation of the hydrogen protons and electrons together with the oxygen molecule and the formation of one water molecule. The potentials in each case are given with respect to the standard hydrogen electrode.

# 1.5

# DISTRIBUTED GENERATION

To meet the system operational requirements, a fuel cell DG system needs to be interfaced through a set of power electronic devices. The interface is very important as it affects the operation of the fuel cell system as well as the power grid.

Various power electronic circuits have been proposed in recent work to interface different energy sources with the utility grid. Pulse-width modulated voltage source inverters (VSI) are widely used to interconnect a fuel cell energy system to a utility grid for real and reactive power control purposes. In addition, fuel cell systems normally need boost dc/dc converters to adapt the fuel cell output voltage to the desired inverter input voltage and smooth the fuel cell output current.

Fig. 1.2 shows the schematic diagram of the fuel cell DG system. The system configuration ratings and parameters are given in Table 1.1. The PEMFC power plant consists of ten fuel cell arrays connected in parallel. Each array is rated at 48 kW, for a total of 480 kW. A boost converter is used to adapt the output voltage of each fuel cell array to the dc bus voltage. The dc bus voltage (dc/dc converter output) is chosen as $V_{DC}$= 480V, which is mainly determined by the inverter ac output voltage and the voltage drop across the LC filter.

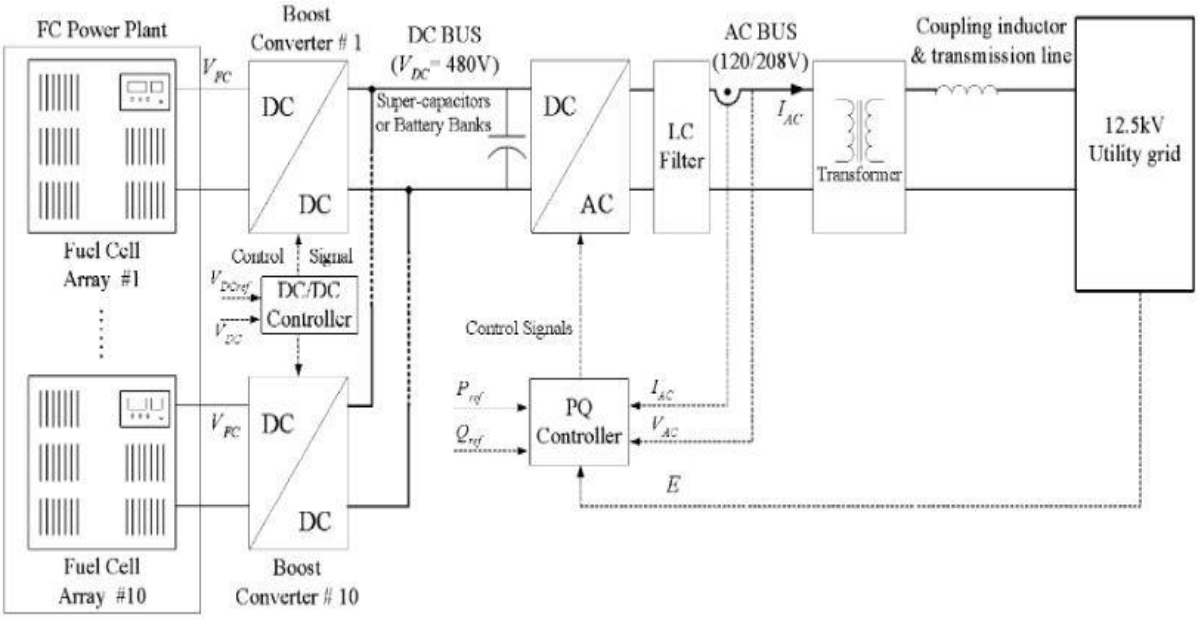



***Fig: 1.2*** *Block Diagram of a Fuel Cell Distributed Generation System*

| | |
|---|---|
| PEMFC Power Plant | 216V/480kW<br>Ten 48-kW FC arrays are connected in parallel |
| PEMFC Array | 216 V/48 kW, consisting of<br>8(series) × 12 (parallel) 500-W fuel cell stacks |
| Boost dc/dc Converter | 200 V/480 V, 50 kW each.<br>10 units connected in parallel. |
| 3-phase dc/ac Inverter | 480 V dc/208 V ac, 500 kW |
| LC Filter | $L_f$ = 0.15 mH, $C_f$ = 306.5 uF |
| Step-Up Transformer | $V_n$ = 208 V/12.5 kV, $S_n$ = 500 kW<br>$R_1 = R_2$ = 0.005 p.u., $X_1 = X_2$ = 0.025 p.u. |
| Coupling Inductor | $X_c$ = 50 Ω |
| Transmission Line | 0.5 km ACSR 6/0<br>$R$ = 2.149 Ω/km, $X$ = 0.5085 Ω/km |
| DC Bus Voltage | 480 V |
| AC Bus Voltage | 120 V/208 V |

***Table 1.1:*** *System configuration ratings and parameters*

# Chapter 2

# PEM Fuel Cell Model Simulated in MATLAB

## 2.1 Output voltage and power control using PI controller

### 2.1.1 PEM Fuel Cell Model

### 2.1.2 Fuel Cell Reformer Model

### 2.1.3 Power Conditioning Unit/Inverter Model

## 2.2 Output voltage and power control using NN controller

# 2.1

# PEM FC MODEL WITH OUTPUT VOLTAGE AND POWER CONTROL USING PI CONTROLLER

## 2.1.1 PEM FUEL CELL MODEL

The proportional relationship of the flow of gas through a valve with its partial pressure can be listed as:

$$\frac{q_{H_2}}{p_{H_2}} = \frac{k_{an}}{\sqrt{M_{H_2}}} = k_{H_2} \quad (2.1) \qquad \frac{q_{H_2O}}{p_{H_2O}} = \frac{k_{an}}{\sqrt{M_{H_2O}}} = k_{H_2O} \quad (2.2)$$

Where $qH_2$ is molar flow of hydrogen, $qH_2O$ molar flow of water, $pH_2$ hydrogen partial pressure, $pH_2O$ water partial pressure, $kH_2$ hydrogen valve molar constant, $k_{H2O}$ water valve molar constant, $k_{an}$ anode valve constant, $M_{H2}$ molar mass of hydrogen, $M_{H2O}$ molar mass of water.

For hydrogen, the derivative of the partial pressure can be calculated using the perfect gas equation as follows:

$$\frac{d}{dt} p_{H_2} = \frac{RT}{V_{an}} (q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}) \quad (2.3)$$

Where R is the universal gas constant, T absolute temperature, $V_{an}$ volume of the anode, $qH^{in}_2$ hydrogen input flow, $qH^{out}_2$ hydrogen output flow, $qH^{r}_2$ hydrogen flow that reacts.

The relationship between the hydrogen flow and the stack current can be written as:

$$q_{H_2}^{r} = \frac{N_o I}{2F} = 2k_r I \quad \textbf{(2.4)}$$

Using the above equation, the differential equation for hydrogen can be written in *s* domain as:

$$p_{H_2} = \frac{1/k_{H_2}}{1 + \tau_{H_2} s}(q_{H_2}^{in} - 2k_r I) \quad \textbf{(2.5)}$$

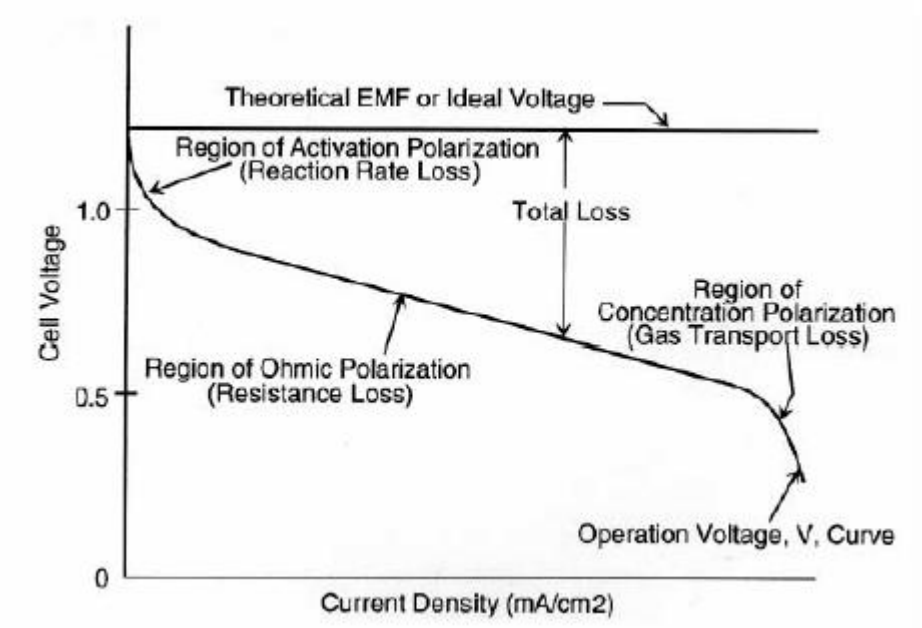



***Fig: 2.1*** *Fuel Cell Polarisation Curve*

Where B = 0.04777 V and C = 0.0136 $A^{-1}$ are constants. The Nernst voltage in terms of gas molarities can be written as:

$$E = N_o \left[ E_o + \frac{RT}{2F} log \left[ \frac{p_{H_2} p_{O_2}^{0.5}}{p_{H_2O}} \right] \right] \quad \textbf{(2.6)}$$

Where E*o* is the open cell voltage and R is the universal gas constant.

In **[1]**, the authors introduced a model that describes the polarisation curves for the PEM fuel cell where the fuel cell voltage is the sum of three terms, the Nernst instantaneous voltage E in terms of gas molarities, activation over voltage $\eta_{act}$, and ohmic over voltage $\eta_{ohmic}$. In mathematical form, polarization curves can be expressed by the equation:

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} \quad \textbf{(2.7)}$$

Where, $\eta_{act}$ is a function of the oxygen concentration $CO_2$ and stack current $I$, and $\eta_{ohmic}$ is a function of the stack current and the stack internal resistance $R_{int}$. Assuming constant temperature and oxygen concentration, the above equation can be written as:

$$V_{cell} = E - B\ln(CI) - R^{int}I \quad \textbf{(2.8)}$$

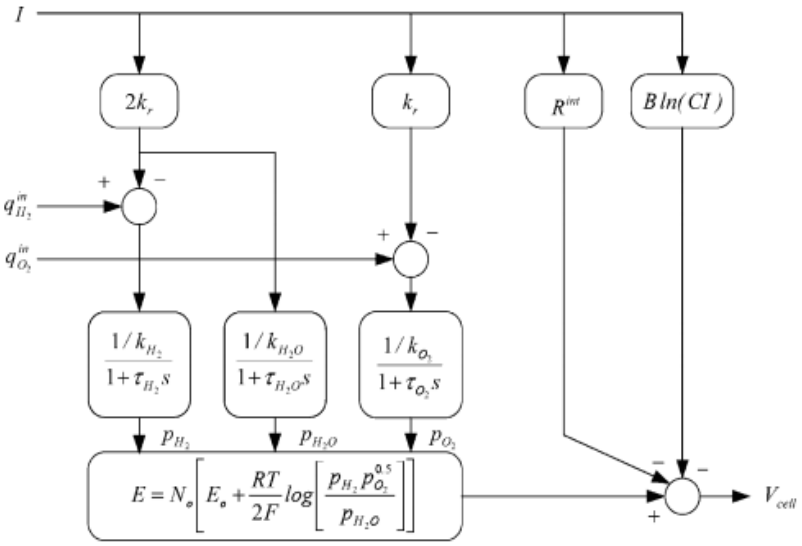



***Fig: 2.2*** *Fuel Cell Model*

## 2.1.2 PEM FUEL CELL REFORMER MODEL

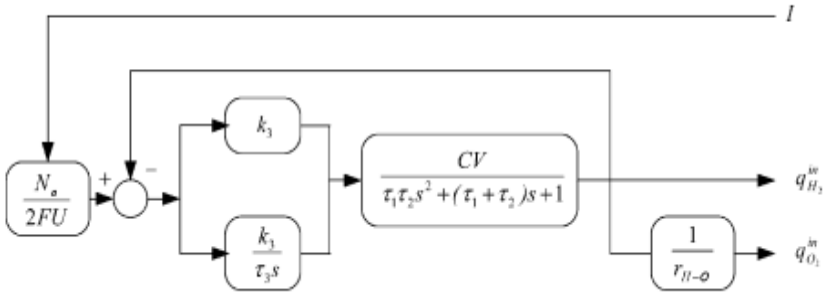



***Fig: 2.3*** *Reformer Model*

Figure 2.3 shows a simple model of a reformer that generates hydrogen through reforming methanol. The mathematical form of the model can be written as follows:

$$\frac{q_{\mathrm{H_2}}}{q_{\mathrm{methanol}}} = \frac{CV}{\tau_1\tau_2 s^2 + (\tau_1 + \tau_2)s + 1} \quad \textbf{(2.9)}$$

Where $q_{\mathrm{methanol}}$ is methanol flow rate, $CV$ conversion factor, $\tau_1$, $\tau_2$ are time constants. The amount of hydrogen required to meet the load change can be used to control the methanol flow rate as shown below:

$$q_{\mathrm{methanol}} = \left(k_3 + \frac{k_3}{\tau_3 s}\right)\left(\frac{N_o I}{2\mathrm{FU}} - q^{\mathrm{in}}_{\mathrm{H_2}}\right) \quad \textbf{(2.10)}$$

## 2.1.3 POWER CONDITIONING UNIT/INVERTER MODEL

The power conditioning model of our fuel cell is shown below [1]. It uses a PI controller in order to control the output voltage and power.

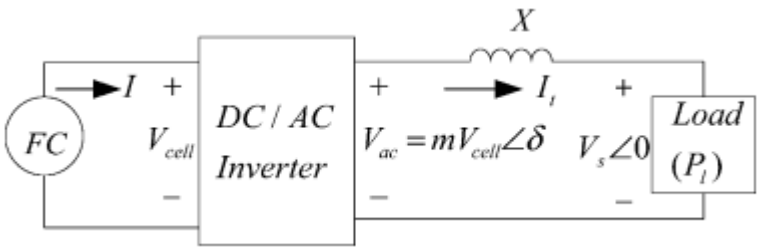



***Fig: 2.4*** *Fuel Cell, inverter and load connection*

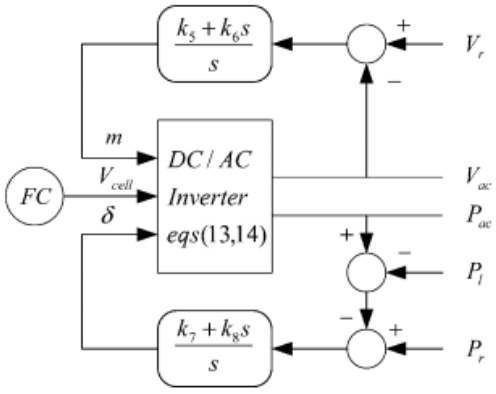



***Fig: 2.5*** *Inverter model*

The relevant equations are given below [1]:

$$V_{ac} = m V_{cell} \angle \delta \quad \textbf{(2.11)}$$

$$P_{ac} = \frac{m V_{cell} V_s}{X} \sin(\delta) \quad \textbf{(2.12)}$$

$$I_t = \frac{P_l}{(V_s \cos(\theta))} \quad \textbf{(2.13)}$$

$$I = m I_t \cos(\theta + \delta) \quad \textbf{(2.14)}$$

$$m = \frac{k_5 + k_6 s}{s}(V_r - V_{ac}) \quad \textbf{(2.15)}$$

$$\delta = \frac{k_7 + k_8 s}{s}(P_r - P_{ac} + P_l) \quad \textbf{(2.16)}$$

Where $V_{ac}$ is ac output voltage of the inverter, $m$ inverter modulation index, $\delta$ is the phase angle of the ac voltage, $P_{ac}$ is the ac output power from the inverter, $V_s$ load terminal voltage, $X$ reactance of the line connecting the fuel cell and the load, $I_t$ load current, $\vartheta$ load phase angle and $P_l$ load power.

| Model Parameters | |
|---|---|
| Stack Temperature, (K) | 343 |
| Faraday's constant, $F$ (C kmol$^{-1}$) | 96484600 |
| Universal gas constant, $R$ (J kmol$^{-1}$ K) | 8314.47 |
| No load voltage, $E_o$, (V) | 0.6 |
| Number of cells, $N_o$ | 88 |
| $K_r$ constant = $N_o/4F$ (kmol s$^{-1}$ A) | $0.996 \times 10^{-6}$ |
| Utilization factor, $U$ | 0.8 |
| Hydrogen valve constant, $K_{H2}$ (kmol s$^{-1}$ atm) | $4.22 \times 10^{-5}$ |
| Water valve constant, $k_{H_2O}$ (kmol s$^{-1}$ atm) | $7.716 \times 10^{-6}$ |
| Oxygen valve constant, $k_{O_2}$ (kmol s$^{-1}$ atm) | $2.11 \times 10^{-5}$ |
| Hydrogen time constant, $\tau_{H_2}$ (s) | 3.37 |
| Water time constant, $\tau_{H_2O}$ (s) | 18.418 |
| Oxygen time constant, $\tau_{O_2}$ (s) | 6.74 |
| Reformer time constant, $\tau_1$ (s) | 2 |
| Reformer time constant,$\tau_2$ (s) | 2 |
| Conversion Factor, $CV$ | 2 |
| Activation voltage constant, $B$ (A$^{-1}$) | 0.04777 |
| Activation voltage constant, $C$ (V) | 0.0136 |
| Stack internal resistance, $R^{int}$ ($\Omega$) | 0.00303 |
| Line reactance, $X$ ($\Omega$) | 0.05 |
| PI gain constants $k_5$, $k_6$ | 10 |
| Voltage reference signal, $V_r$ (p.u) | 1.0 |
| Methane reference signal, $Q_{methref}$ (kmol s$^{-1}$) | 0.000015 |
| Hydrogen-oxygen flow ratio, $r_{h-o}$ | 1.168 |

***Table: 2.1*** *List of constants*

Using all the above equations and table 2.1, a program was written in MATLAB and the simulation results are shown below:

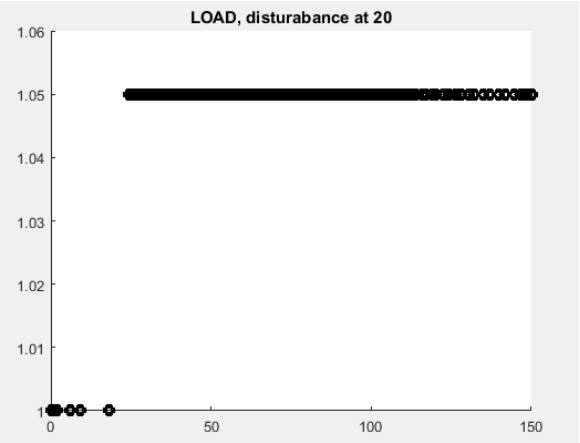



***Fig: 2.6*** *Load vs t*

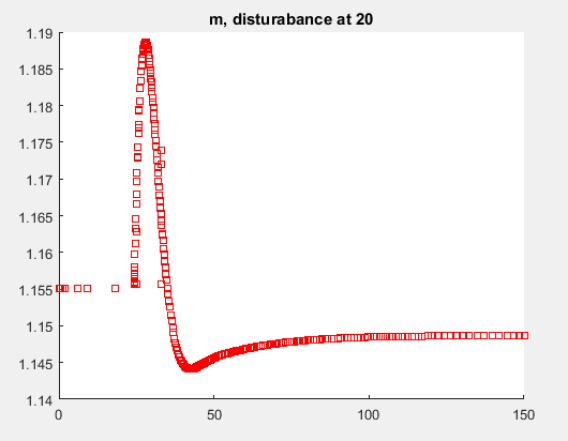



***Fig: 2.7*** *modulation index vs t*

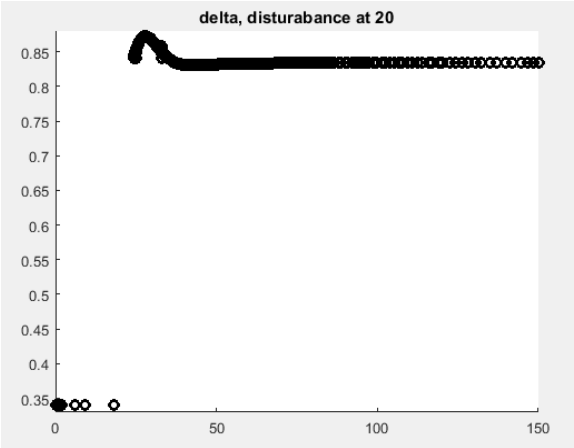



***Fig: 2.8*** *delta vs t*

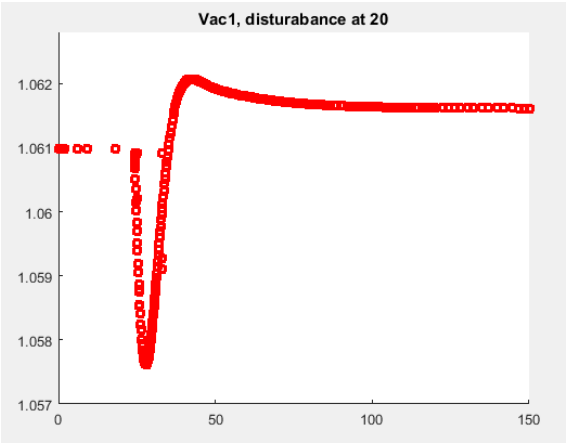



***Fig: 2.9*** *Vac vs t*

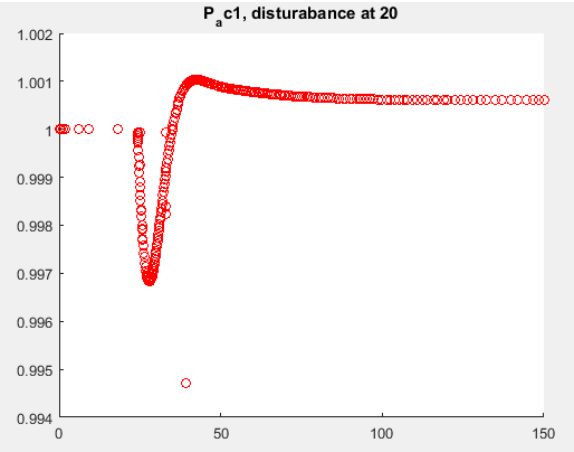



***Fig: 2.10*** *Pac vs t*

# 2.2

# PEM FC MODEL WITH OUTPUT VOLTAGE AND POWER CONTROL USING NN CONTROLLER

The task here is to replace the PI controller with a neural network (NN) controller. Using the data collected from the 2.1, a neural network was designed in MATLAB using Neural Network Fitting tool to control the output voltage and power.

Neural Networks are computing systems inspired by the biological neural networks that constitute animal brains. Such systems learn (progressively improve performance) to do tasks by considering examples, generally without task-specific programming.

A NN is based on a collection of connected units called artificial neurons (analogous to biological neurons in an animal brain). Each connection (synapse) between neurons can transmit a signal to another neuron. The receiving (postsynaptic) neuron can process the signal(s) and then signal downstream neurons connected to it. Neurons and synapses may also have a weight that varies as learning proceeds, which can increase or decrease the strength of the signal that it sends downstream. Further, they may have a threshold such that only if the aggregate signal is below (or above) that level is the downstream signal sent.

Neural Network generally involves 3 steps: Building, Training and Testing. It also consists of 3 layers: Input, Hidden and Output.

In this model, the output voltage and power are controlled by controlling the modulation index *m* and phase angle of ac output voltage *δ.*

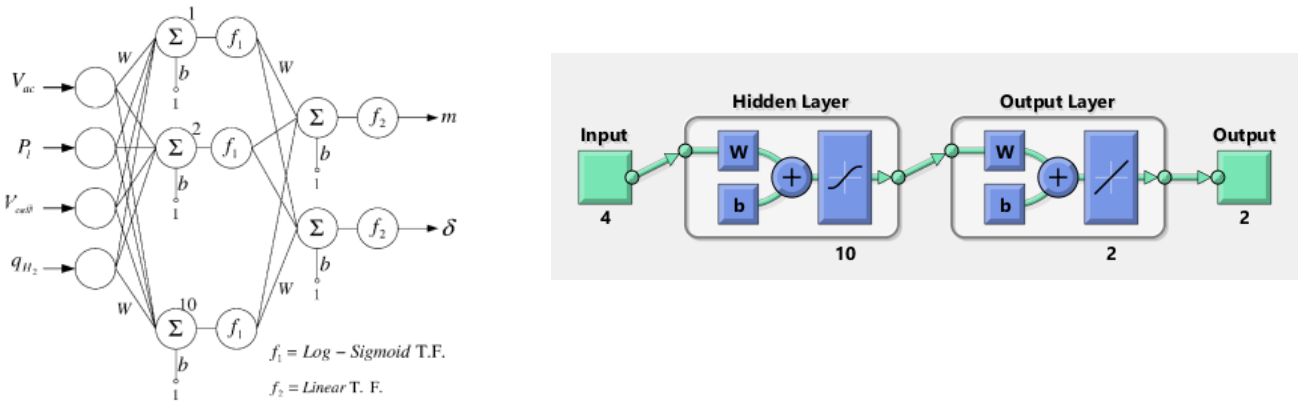



***Fig: 2.11*** *Neural Network Layers*

The network was trained using MATLAB's Neural Network fitting (nftool) using 398 samples of $V_{ac}$, $P_l$, $V_{cell}$ and $q_{h2}$. The hidden layer is composed of 10 neurons and $m$ and $\delta$ were obtained as outputs. Using $m$ and $\delta$, $V_{ac}$ was obtained using equation (2.11).

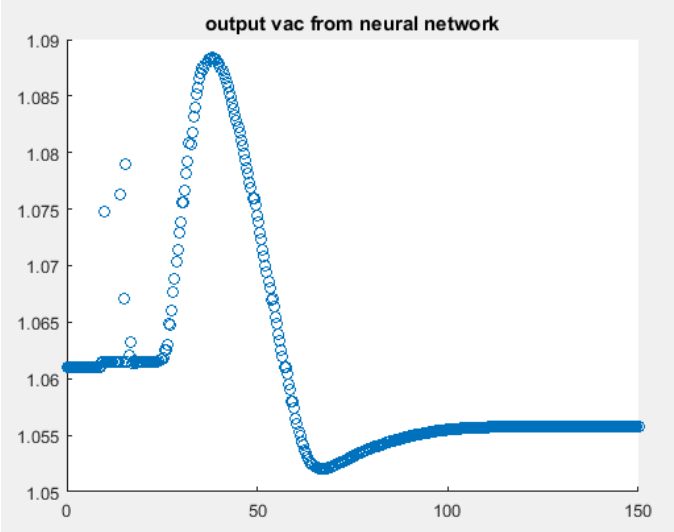



***Fig: 2.12*** *Vac (NN) vs t*

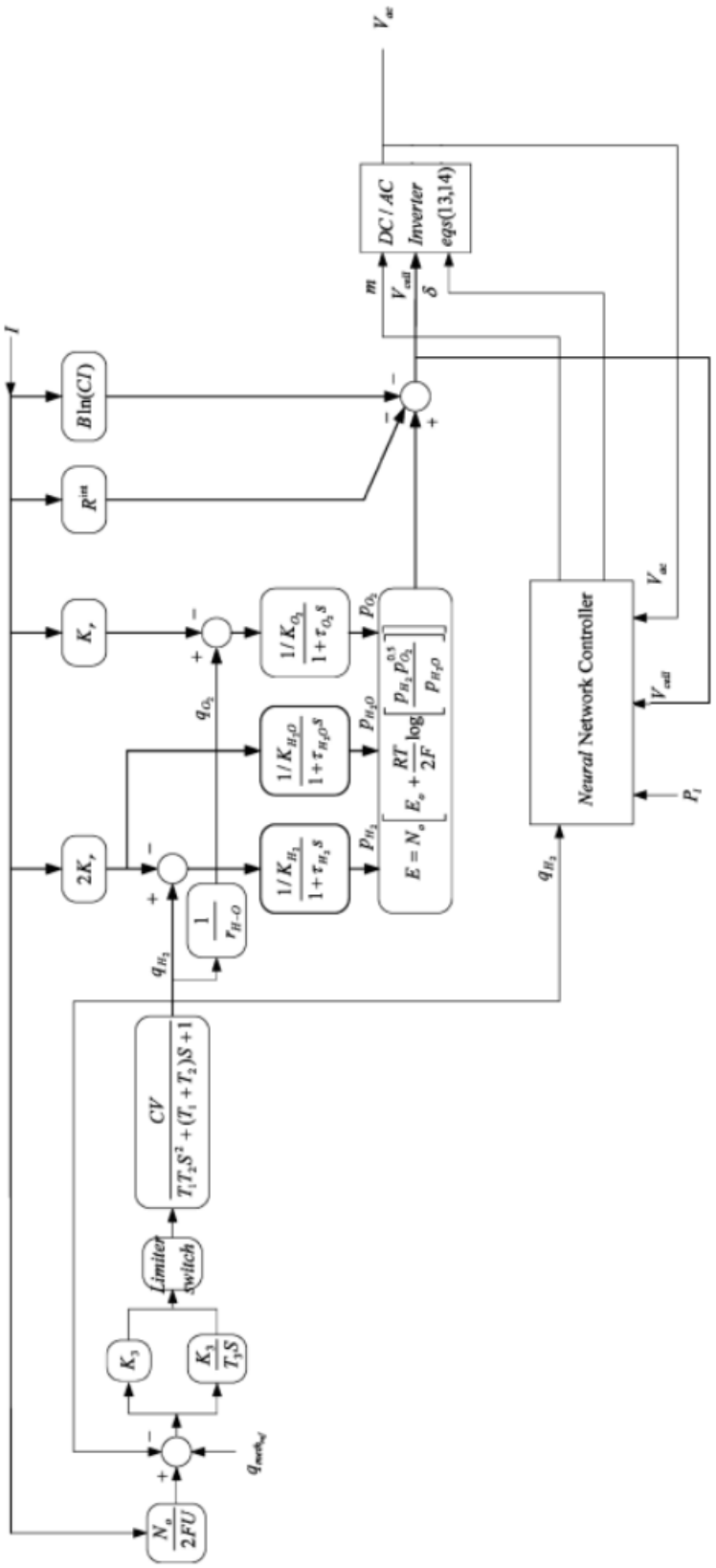


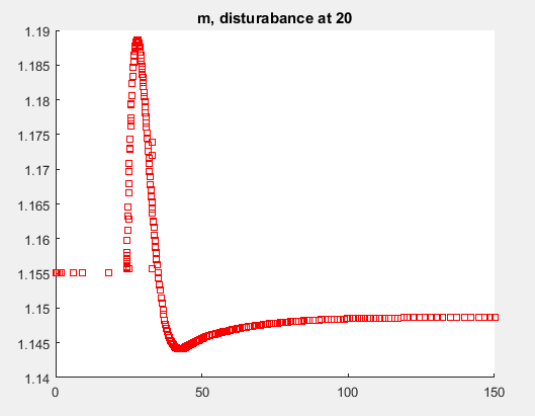

***Fig: 2.13*** *NN model*

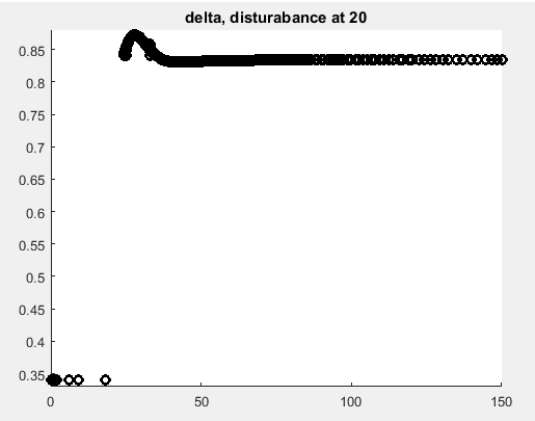
# Chapter 3

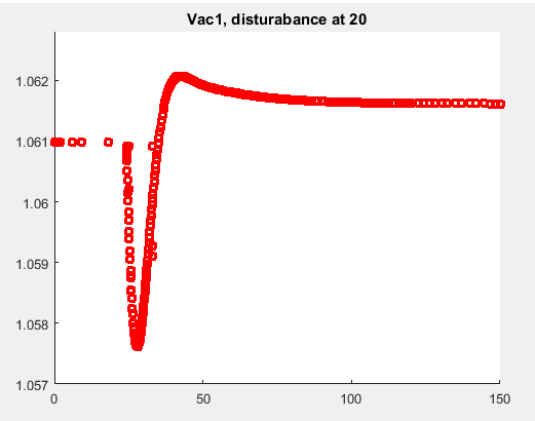
# Comparison and Result

# Comparison and Result

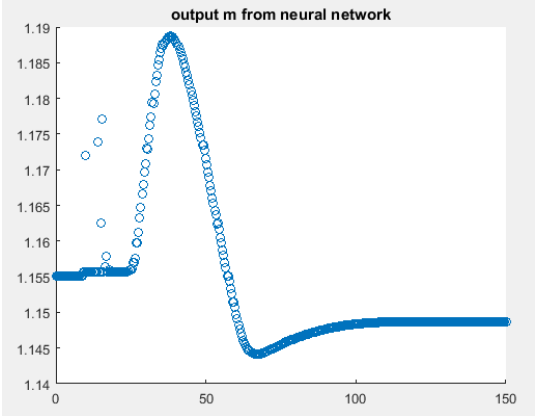
## PI Control

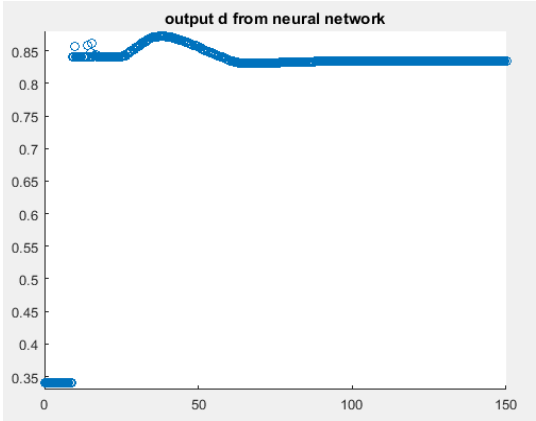



## Neural Network Control



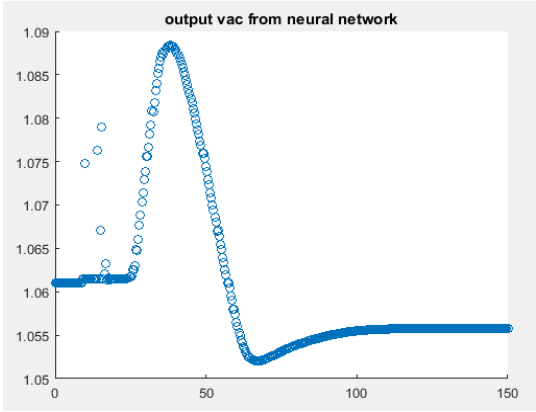




***Fig: 3.1*** *Comparison PI vs NN*

Simulation was done on a desktop computer running an Intel i7 processor @3.4 GHz having 8 GB of RAM.

On comparing the two columns, it's very clear that the setting time of Neural Network is more than PI controller, which is undesirable as a system should settle quickly whenever disturbances are applied.

Also the output voltage from NN can't follow the load properly.

# Chapter 4

# CONCLUSION AND FUTURE WORK

# CONCLUSION AND FUTURE WORK

The performance of our network can be enhanced by increasing the number of samples, which means training the network more thoroughly. The number of neurons in the hidden layer can also be increased but it has been seen that after a certain number, the performance does not change even if the number of neurons are increased. The initial weights, bases and threshold values can be changed also.

In the future, the constants that we have used to design the systems can be optimised using MATLAB's optimisation tool.

Instead of implementing just a neural network, a new technique called **ANFIS** (Adaptive Neuro-Fuzzy Interface System) can be implemented which will make our controller more efficient and robust.

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