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Modelling and Simulation PEM Fuel Cells for Dynamical Electrical Systems in Aircrafts LM-100J Commercial Freighter

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Abstract: ***Dynamics of proton exchange membrane fuel cells (PEMFC) with hydrogen storage system for generating part of airplanes electrical energy is presented. Viability of using fuel cell (FC) for this airplane is estimated by means of simulations. Temperature change and dual layer capacity effect are considered in all simulations. Using a three-level 3-phase inverter, FC's output voltage is connected to the indispensable bus of the airplane. Moreover, it is possible to connect FC's output voltage to airplane DC bus on the other hand. PID controller is presented to control flow of hydrogen and oxygen to FC and improve momentary and steady state responses of the output voltage to load turbulences. FC's output voltage is regulated via an ultra-capacitor. Simulations are carried out in PYTHON and results show that the load tracking and output voltage regulation are acceptable. The proposed system utilizes an electrolyser to generate hydrogen and a tank for storage. Therefore, there is no need for batteries. Moreover, the generated oxygen could be used in other applications in airplane.***

Keywords: python, PID Controller, PEMFC, Simulation graphs, system components of Hercules planes

1. Introduction

In 1956, the US Air Force began development on a Bacon fuel cell for aerospace applications. Development of a reformative fuel cell that can also be used to electrolyze water into hydrogen and oxygen started during the 1960s.In the 1980s, the US Air Force developed fuel cell skill for Alaskan remote radar sites [1]. FCs could generate electricity and heat from chemical processes [2-6]. Their applications have increased knowingly and they could be applied in many industries such as micro-electronics, small boats, airplanes, bus, and combined heat and power (CHP) applications. The results were replacement the alkaline fuel cell (AFC) with a proton exchange membrane (PEM) fuel cell system, resulting in a much lower life cycle cost of the power plant [2-6]. Extra sources which are enormous, consuming, and exclusive is required to start the aircrafts and usually are found in standard airports where LM-100J Commercial Freighter can land .To reduce this problem that one could carry the external source and staff whose cost is high and reduce airplanes efficiency. Moreover, loss of 3 generators is a dangerous case. So it is required to equip airplane with an essential electricity system to enhance reliability. The proposed system includes the mentioned FCs which is connected to DC essential bus via a DC-DC converter or to AC essential bus via a DC-AC converter.

2. System Components

1. FC Model. The used FC is from a PEMFC which includes a single layer electrolyte in contact with anode and cathode The FC Nernst voltage is equal to 1.21 V with H_2O generated [37]. However due to irreversible losses ideal voltage is more than actual voltage.

E_{NERST} is calculated as follow (8):

$$1.2209-0.85\times10^{-3}\ (-2098.15)\ +4.3085\times10^{-3}\ \times T\ \times\ (\ln P_{H2}\ +0.5\ln P_{O2}) \qquad (1)$$

Over voltages due to internal process and resistance are calculated from an experimental equation:

$$\gamma_{act} = -0.9514+0.003120\times\ln(i)+7.4\times 10^{-5} T\times \ln(C_{O2}) \qquad (2)$$

Rin = 0.01605 − 3.5 × 10 − 5T + 8 × 10 − 5i(3)In (3) i is the current flowing in FC and stir resistance is

$$R_a = -\frac{\gamma_{act}}{i} \qquad (4)$$

Coordinated thermodynamic mass transfer and kinetic energy effect determine

FC's voltage is as follows: $V = E-\mu_{act+}\gamma_{ohmic}$ (5)

The voltage drop in FC is compensated by increasing FC's pressure.

The differential equation describing FC's voltage as follows;

$$\frac{d\mu act}{dt} = \frac{i}{C} - \frac{\mu_{act}}{R_{a*C}} \qquad (6)$$

And the ohmic voltage drop is as follows:

$$\gamma_{ohmic} = -i\times R_{in} \qquad (7)$$

The proposed system FC includes 60 series cells. So, it's output voltage is equal to

$$V_{stack} = 120\ \text{cell} \qquad (8)$$

O_2 and H_2 consumption in FC depends on input/output rate and FC's current. Using input/output -rate one can calculate the pressure of the gas (in FC's humidifier) using the mol's equality law, the anode and cathode volume are assumed to be 1.5L. The total balance of the thermal energy in a FC cooled by air can be written as follows:

$$Q_1 = Q_s + Q_L \tag{9}$$

whereQ_1 ,Q_s , andQ_L represent generated, stored, and internal dissipated heat, respectively. To calculate internal loses heat, FC's current and internal resistance are used as below for 120 cells:

internal generated temperature $= i\ 2\ (R_a + \text{Rint}) \times 120.$ (10)

2. Ultracapacitor Model. An ultracapacitor is an energy storage device similar to conventional. These capacitors include two electrodes floating in an electrolyte and they are separated via an isolator. A 430 F and 14.4 V capacitor module is modelled for the proposed system. To reach 41.5V voltage, one can use 5 modules in series. The selected module has 5mΩ series resistance and 10.5 mA leakage current. In simulations, the leakage current is assumed to be constant and the current needed for cooling the system is neglected. Therefore, the capacitor module is modelled by a capacitor in series with a resistance, with 108.55 F capacitance and 15.5 m Ω resistance as shown in below figure;

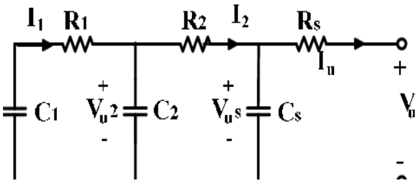

Figure 1: Ultracapacitor

The ultracapacitor is modelled like a low pass filter (LPF)

By the following transfer function [32]:

$$\frac{V_{ucap}}{V_{stack}} = \frac{s+1/(R_S.C)}{s\left(1+\frac{R_S}{R_C}\right)+1/(R_S.C)} \tag{11}$$

3. Dynamic Model Electrolyser. An electrolyser system includes several electrolyser cells connected in series. Their characteristic depends on temperature and usually it is extremely nonlinear and could be obtained by curve fitting. According to Faraday's law, the rate of generating H_2 in electrolyser is proportional to the rate of current flowing in electrodes, which is actually the current in output circuit [12, 13]:

$$€_{H2} = \frac{€_F}{2F}.n_n.i_e \tag{12}$$

In (12)$i_{e,}\, n_n\, €_{H2}$ represent electrolyser's current, number of series electrolysers, and Faraday's efficiency, respectively.

Faraday's efficiency is the ratio of the maximum practical generated H_2 to maximum theoretical possible generation of H_2. Assuming the operation temperature of 40.4℃ , it is equal to

$$€_F = 96.5 \times \exp\left(\frac{0.09}{i_e} - \frac{75.5}{i_e^2}\right) \tag{13}$$

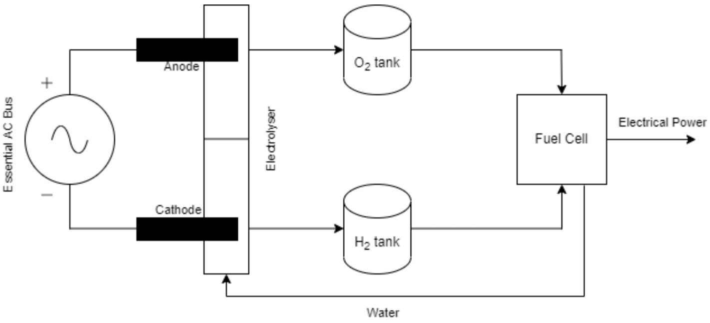

Figure 2: FC, Hydrogen Tank, Oxygen tank, electrolyser

Equations (12) and (.13) represent a simple model of electrolyze assuming that FC has an autonomous cooling system for regulating the temperature at 40. 4℃. Figure2 shows a schematic of a FC connected to electrolyser while the FC's electrical energy is supplied by airplane's essential AC bus.

4. DC-DC Converter Model-, the converter module shown in Figure 3 has two stages for voltage and frequency regulation. First stage is a DC-DC boost converter which regulates the output voltage at a high constant DC voltage while its input is a low varying voltage. This boost converter is controlled by a PID controller in order to regulate the output voltage at 200.4 V.
This can be achieved by proper tuning of (duty cycle) in the following equation:

$$\frac{V_{boost}}{V_{ucap}} = \frac{1}{1-D} \tag{14}$$

To determine the value of conductor invertor capacitor we can use the following equations;

So, one can calculate power inductance and capacitance as below

$$L_C = \frac{k(1-k).R}{2f} = \frac{0.4204 \times (1-0.4204) \times 90}{2 \times 10000} = 1.1 \times 10^{-3}\ \text{H} \tag{15}$$

$$C_C = \frac{V_C.k}{f.R.\Delta V_C} = \frac{625 \times 0.44}{10000 \times 90 \times 5.6} = 54 \times 10^{-6}\text{F} \tag{16}$$

The DC-DC converter pulse generator should satisfy these following duties: maximum power point tracking (MPPT), boosting voltage up to desired level. It is possible to change the inverter output voltage by varying DC bus voltage level. Therefore, for known inverter output voltage level, it is possible to tune DC bus voltage in order to have constant output voltage. In this paper, the inverter output voltage is 230 rms. Therefore, DC bus voltage should be higher than$V_{ab\,1}$;

As shown in figure 4, the DC bus voltage is compared to reference 200.4 V and their discrepancy is passed to a controller in order to be amplified. Afterwards, to have a

200.4output voltage, the resulting error is added to the reference 200.4 V signal and results in V_{ds} signal. Figure 4 shows the procedure of the duty cycle calculator. In this figure, the Vbus, ref signal is divided into $_{MPP}$ to determine the duty cycle. Moreover, there are solutions in that block to prevent exceeding [0-1] range and fast variations. The resulting duty cycle passes to pulse generator which should generate signals for IGBT Switches.

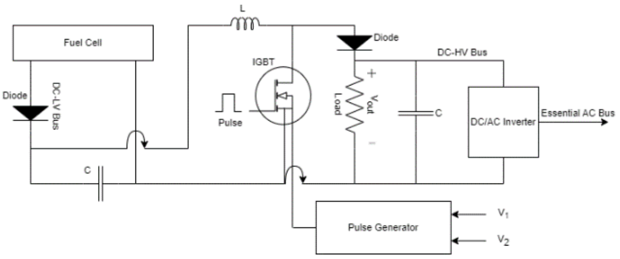

Figure 3: FC connection to AC BUS

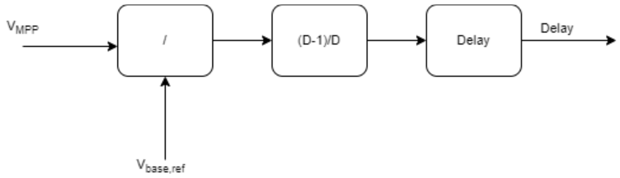

Figure 4: Duty cycle calculator

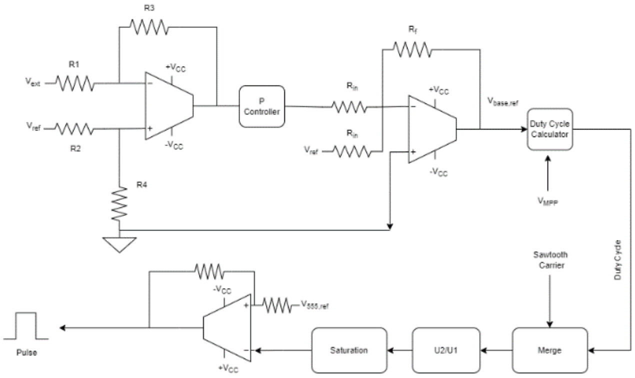

Figure 5: Pulse generator

PWM technique is implemented to generate pulses. Saw-tooth carrier frequency is 10kHz. Afterwards, the generated pulse is used to control DC-DC converter. These two blocks-duty cycle calculator and pulse generator-act as actuator in this closed loop control system.

5. Inverter Model

The inverter uses a PWM technique with triangle carrier signal frequency of 8.5 kHz. Regarding circuit properties, medium power rate, high frequency switching, and high input voltage, a three-level converter is used with IGBT switches. The inverter voltage has large harmonic contents that should be eliminated. According to IEEE standard 519.1992, the THD voltage should be less than 5% and usually needs appropriate use of filters. Since voltages are sinusoidal, odd harmonics are important, so the 3rd-9th order harmonics, 11th-15th harmonics, and 17th-21th harmonics should be less than 4%, 2%, and 1.5%, respectively. To control the current, a close loop current controller is used. This control system receives $I_{d\,\mathrm{ref}}$ and $I_{q\,\mathrm{ref}}$ from an outer control loop and compares them with actual values. As shown the actual inverter current is measured and transferred to d_q0 frame via a PLL. One could change active/reactive power with proper setting of$I_{d\,\mathrm{ref}}$ and $I_{q\,\mathrm{ref}}$ while $_{\mathrm{ref}}$ is usually set to zero. Moreover, there is a closed loop system which adds the $I_{d\,,\mathrm{error}}$ to$I_{d\,\mathrm{ref}}$.$I_{d\,\mathrm{ref}}$ and$I_{q\,\mathrm{ref}}$is passed to comparator from a compensator block which naturally is exponential and it is compared to the actual value there. Finally, the error signal is passed to PID controller and passes to - transformation block to generate the reference signal for PWM switching. Therefore, PWM switching technique controls the inverter output voltage in order to generate the desired power.

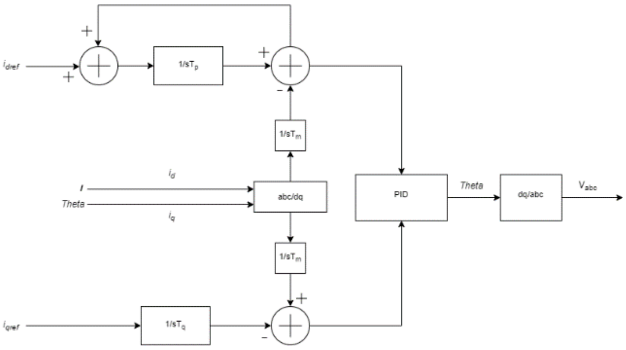

Figure 6: Inverter control system

Due to nonlinear nature of system, slow response of system to load changes, and substantial steady state error, there is essential need for a PID controller:

$$G_r(s) = (s + T_d^{s^2} + \frac{1}{T_i})\frac{k_D}{s} \quad (17)$$

This controller controls its output voltage with varying the input hydrogen and oxygen flow. Also, limiter is used to limit the gas pressure in FC. Ziegler-Nichol's solution is used to set PID controller parameters are listed in TABLE

PID Control parameters are given in table along.

H_2	O_2	Constants
5.50	2.20	Kp
0.5	0.5	T_i
0	0	T_d

6. Hydrogen Tank

We have stored hydrogen at high pressure approximately up to 300atm. Due to advances in composite materials there are800atm storage tanks available.

3. Results

The model is simulated PYTHON. The simulation model includes 8 subsystems: FC, electrolier, ultra-capacitor, inverter, booster, H_2 storage, and H_2 and O_2 rate of low controller. Each subsystem is a model containing its mathematical equations. A 3-phase inverter is used after

DC-DC converter to connect it to AC bus. The graphs plotted show DC-DC converter's output voltage, filtered voltage, and applied voltage to load and load current. Using fuel cell in an electrical backup system improves the reliability of electrical system and based on the fly ability is increased. The FC system could generate the oxygen usage for flight personnel. FC application in Hercules causes better flight performance and external generator can be removed accordingly. In emergency cases, FC installation can help the pilot in hydraulic and electric failures. Simulation results successfully show ability of the proposed system in Hercules application. Figures8, 9, 10, 11, 12, 13, show DC-DC converter's output voltage filtered voltage, and applied voltage to load and load current. Figure 12 shows the inverter current for worst case circumstance. Moreover, Figure 13 shows the Inverter's 3-phase output current for best THD circumstance. As shown in Figure6.5, current injected to system is low. The codes are developed in PYTHON by the help of tools and the results are shown as graphs. The variables are randomly selected within specified range.

Source Code

```
#!/usr/bin/env python
# coding: utf-8
# In[42]:
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd
import random
# Code 1
df_1 = pd.read_csv("data_for_graph8.csv",header=None)
df_1.columns = ["Time (s)","Boost coil current"]
df_1.sort_values(by=["Time (s)"],inplace=True)
ax = df_1.plot(kind="line",x="Time (s)",y="Boost coil current",yticks=range(0,15),xticks=np.arange(0,2.01,0.2))
ax.set_xlabel("Time (s)")
ax.set_ylabel("Boost coil current")

# Code 2
df_2 = pd.read_csv("data_for_graph9csv",header=None)
df_2.columns = ["Time (s)","Output voltage of Boost converter"]
df_2.sort_values(by=["Time (s)"],inplace=True)
ax = df_2.plot(kind="line",x="Time (s)",y="Output voltage of Boostconverter",xticks=np.arange(0,2.01,0.2))
ax.set_xlabel("Time (s)")
ax.set_ylabel("Output voltage of Boost converter")

# Code 3
def data_for_graph10()
    x = np.arange(0,0.4,0.001)
    y = []
    for t in x:
        if t < 0.025: y.append(random.choice([100,210]))
        if 0.025 <= t and t < 0.05: y.append(random.choice([0,100]))
        if 0.05 <= t and t < 0.075: y.append(random.choice([0,-100]))
        if 0.075 <= t and t < 0.1: y.append(random.choice([-100,-200]))
        if 0.1 <= t and t < 0.125: y.append(random.choice([-100,-200]))
        if 0.125 <= t and t < 0.15: y.append(random.choice([0,-100]))
        if 0.15 <= t and t < 0.175: y.append(random.choice([0,100]))
        if 0.175 <= t and t < 0.2: y.append(random.choice([100,200]))
        if 0.2 <= t and t < 0.225: y.append(random.choice([100,200]))
        if 0.225 <= t and t < 0.25: y.append(random.choice([0,100]))
        if 0.25 <= t and t < 0.275: y.append(random.choice([0,-100]))
        if 0.275 <= t and t < 0.3: y.append(random.choice([-100,-200]))
        if 0.3 <= t and t < 0.325: y.append(random.choice([-100,-200]))
        if 0.325 <= t and t < 0.35: y.append(random.choice([0,-100]))
        if 0.35 <= t and t < 0.375: y.append(random.choice([0,100]))
        if 0.375 <= t and t < 0.4: y.append(random.choice([100,200]))
    return pd.DataFrame({"Time (s)":x,"Output Voltage of Phase to Phase V_BC":y})

df_3 = data_for_graph10 ()
df_3.sort_values(by=["Time (s)"],inplace=True)
ax = df_3.plot(kind="line",x="Time (s)",y="Output Voltage of Phase to Phase V_BC",yticks=range(-300,400,100))
```

```
ax.set_xlabel("Time (s)")
ax.set_ylabel("Output Voltage of Phase to Phase V_BC")
# Code  4
def data_for_graph11
    x = np.arange(0,0.4,0.001)
    y = []
    for t in x:
        if t < 0.025: y.append(random.choice([0,-100]))
        if 0.025 <= t and t < 0.05: y.append(random.choice([0,100]))
        if 0.05 <= t and t < 0.075: y.append(random.choice([100,200]))
        if 0.075 <= t and t < 0.1: y.append(random.choice([100,200]))
        if 0.1 <= t and t < 0.125: y.append(random.choice([100,0]))
        if 0.125 <= t and t < 0.15: y.append(random.choice([0,-100]))
        if 0.15 <= t and t < 0.175: y.append(random.choice([-100,-200]))
        if 0.175 <= t and t < 0.2: y.append(random.choice([-100,-200]))
        if 0.2 <= t and t < 0.225: y.append(random.choice([-100,0]))
        if 0.225 <= t and t < 0.25: y.append(random.choice([0,100]))
        if 0.25 <= t and t < 0.275: y.append(random.choice([100,200]))
        if 0.275 <= t and t < 0.3: y.append(random.choice([100,200]))
        if 0.3 <= t and t < 0.325: y.append(random.choice([100,0]))
        if 0.325 <= t and t < 0.35: y.append(random.choice([0,-100]))
        if 0.35 <= t and t < 0.390: y.append(random.choice([-100,-200]))
        if 0.390 <= t and t < 0.4: y.append(random.choice([-100,0]))
    return pd.DataFrame({"Time (s)":x,"Output Voltage of Phase to Phase V_AB":y})

df_4 = data_for_graph11()
df_4sort_values(by=["Time (s)"],inplace=True)
ax = df_4.plot(kind="line",x="Time (s)",y="Output Voltage of Phase to Phase V_AB",yticks=range(-300,400,100))
ax.set_xlabel("Time (s)")
ax.set_ylabel("Output Voltage of Phase to Phase V_AB")

# Code 5
x = np.arrange(0,0.4,0.002)
y1 = np.sin((x+np.pi/3)*np.pi*10)
y2 = np.sin((x)*np.pi*10)
y3 = np.sin((x+2*np.pi/3)*np.pi*10)
y1 = [el + np.random.normal(0,0.15) for el in y1 ]
y2 = [el + np.random.normal(0,0.15) for el in y2 ]
y3 = [el + np.random.normal(0,0.15) for el in y3 ]
df_5 = pd.DataFrame({"Time (s)":x,"Phase 1":y1,"Phase 2":y2, "Phase 3":y3})
plt.plot(x, y1)
plt.plot(x, y2)
plt.plot(x, y3)
plt.xlabel('Time (s)')
plt.ylabel('Three phase current output of DC/AC inverter')
plt.show()

# Code  6
x = np.arrange(0,0.4,0.004)
y1 = np.sin((x+np.pi/3)*np.pi*10)
y2 = np.sin((x)*np.pi*10)
y3 = np.sin((x+2*np.pi/3)*np.pi*10)
y1 = [el + np.random.normal(0,0.04) for el in y1 ]
y2 = [el + np.random.normal(0,0.04) for el in y2 ]
y3 = [el + np.random.normal(0,0.04) for el in y3 ]
df_6 = pd.DataFrame({"Time (s)":x,"Phase 1":y1,"Phase 2":y2, "Phase 3":y3})
plt.plot(x, y1)
plt.plot(x, y2)
plt.plot(x, y3)
plt.xlabel('Time (s)')
plt.ylabel('Three phase current output of DC/AC inverter')plt.show()
```

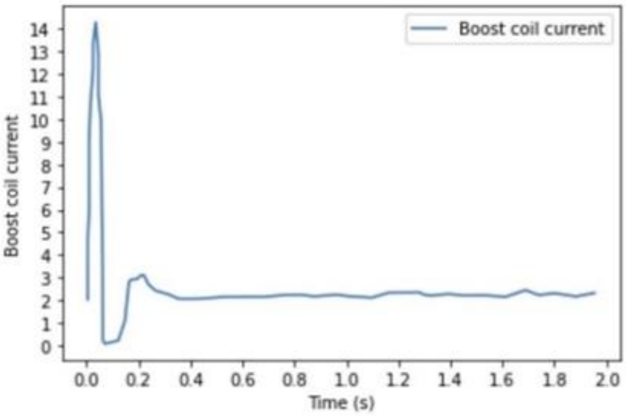

Figure 8: boost coil current

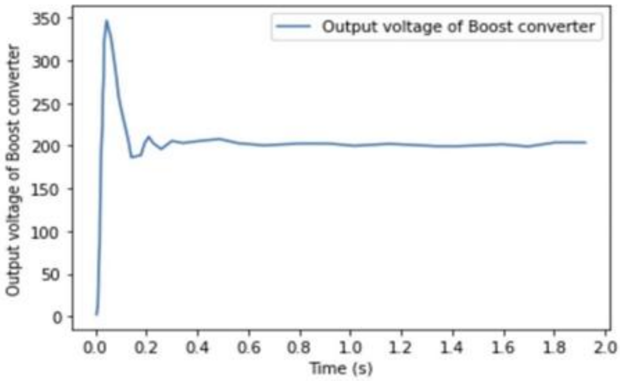

Figure 9: output voltage of DC-DC converter

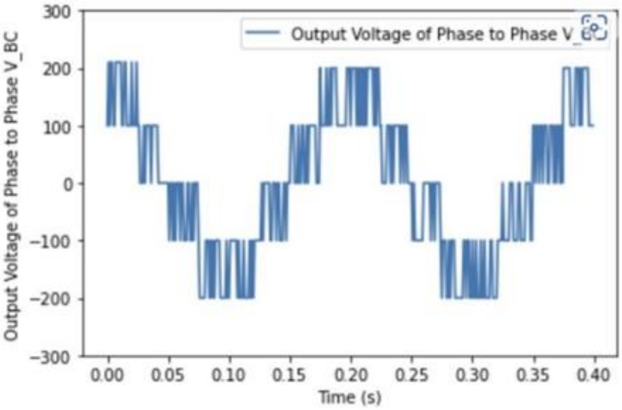

Figure 10: line to line B-C voltage of inverter

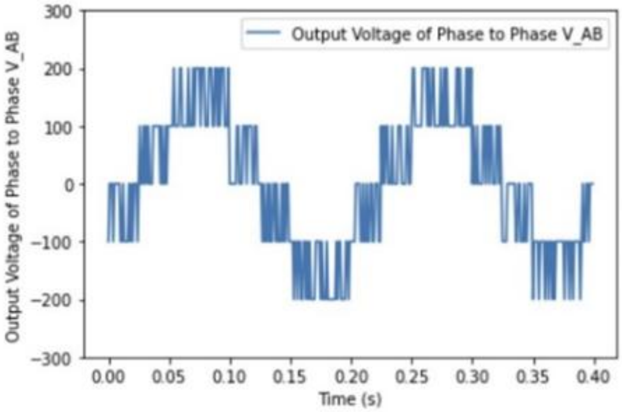

Figure 11: line to lineA-B voltage of inverter

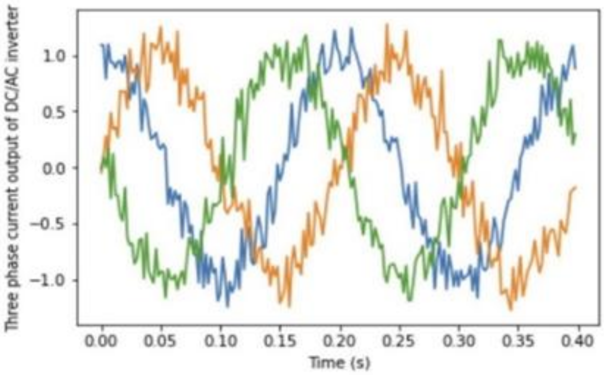

Figure 12: Inverter’s output current in worst case THD

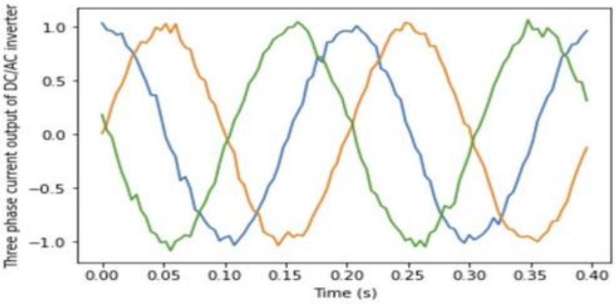

Figure 13: Inverter’s output current in best THD

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