Modeling and Simulation of PEM Fuel Cell Generator as a Micro Grid

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Abstract— This paper describes an integrated model for a Photon Exchange Membrane (PEM) fuel cell generator including the power conditioning devices that can be used as a micro grid. The main focus here is the development of a detailed model of the fuel cell, power conditioning devices and a Voltage Source Inverter (VSI) with no major assumptions. To this end nonlinear models for PEM fuel cell generator, power conditioning devices and controllers are designed and built in Matlab® and Simulink® and the integrated designs are validated. Then several case studies are performed to operate the proposed integrated model as a micro-grid. Overall vision is to validate this model with real-life system and generate smart controller for the micro-grid that could be implemented in real-time as a Distributed Generator (DG).

Keywords—component; PEM Fuel cell, DC/DC Converter, VSI Inverter, Micro-grid, Smart-Grid, Distributed Generator (DG)

I. NOMENCLATURE

Parameter	Value
Number of Cells per Stack (N_o)	88
Number of Stacks (N_{stack})	1
Faraday's Constant (F)	96484600 C kmol ⁻¹
Utilization Factor (U)	0.8
k_3 constant = $1/(2CV)$	0.25
Reformer Time Constant (τ_1)	2
Reformer Time Constant (τ_2)	2
PI Controller Time Constant (τ_3)	2
Conversion Factor (CV)	2
Methane Reference Signal ($q_{methref}$)	15*e ⁻⁶
Hydrogen-Oxygen Flow Ratio (r_{H-O})	1.168
k_r constant = $No/(2F)$	966*e ⁻⁹
Stack Internal Resistance (R^{int})	303*e ⁻⁵
Activation Voltage Constant (B)	4777*e ⁻⁵
Ohmic Resistance Inside Cell (R_{ohm})	0.2793
Constant Factor (λ_c)	333*e ⁻⁵
Overall Flow Delay (τ_c)	80
Activation Voltage Constant (C)	0.0136
Hydrogen Valve Constant (K_{H_2})	422*e ⁻⁷
Oxygen Valve Constant (K_{O_2})	211*e ⁻⁷
Water Valve Constant (K_{H_2O})	7716*e ⁻⁹
Hydrogen Time Constant (τ_{H_2})	3.37
Oxygen Time Constant (τ_{O_2})	6.74
Water Time Constant (τ_{H_2O})	18.418
Standard No Load Voltage (E_o)	0.8
Universal Gas Constant (R)	8314.47
Stack Temperature (T)	343
Line Reactance (X)	0.05

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Source Voltage (V_s)	120
PI Gain Constants (k_s, k_e)	10
Empirical Constant (k_{RI})	1872*e ⁻⁶
Empirical Constant (k_{RT})	-23712*e ⁻⁷

II. INTRODUCTION

A fuel cell generator in the form of a micro grid can be represented as shown in fig. 1 block diagram. Main components consist of fuel cell stack, power conditioning devices such as DC/ DC Converters and inverter with controllers for fuel cell and VSI Inverter. Each of these blocks is discussed next.

Figure 1. Block diagram of a fuel cell generator

A. Fuel Cell Generator

A PEM Fuel Cell is comprised of two main components, the reformer and fuel cell stack. The reformer is the component that takes hydrocarbons, in most cases, such as methanol or propane and separates the hydrogen molecules from the gases and injects that into the anode side of the fuel cell stack. In the anode, hydrogen is forced through a catalyst, usually made of platinum, which separates the hydrogen molecules into electrons and protons. The protons are allowed to permeate through a proton conducting polymer membrane called a Proton Exchange Membrane (PEM), which separates the anode and cathode. The electrons are forced around the electrically insulated PEM through an external circuit which in turn supplies electrical power to it. An elementary block diagram is given in fig. 2. Several models have been proposed for the fuel cell [1]-[12]. However, most of these models shows the basic equations for the fuel cells with some assumptions or do not consider the power conditioning devices to use this system as a micro grid. The proposed model of the fuel cell is an electromechanical one with no major assumptions and reflecting the nonlinear relation between chemical reactions in the fuel cell. Also the model presented here is based on

simulating the relationship between output voltage and partial pressures of hydrogen, oxygen, and water. It gives insight to the transient and linear response of a PEM fuel cell with a generating capacity of one thousand watts.

Figure 2. Elementary flow block diagram of a PEM fuel cell

In fig. 2, the reformer provides relatively pure hydrogen to the fuel cell, using a hydrocarbon that is readily available such as methanol, propane, or natural gas to name a few. For houses and stationary power generation, fuels like natural gas or propane are preferred, simply because many power generator stations and houses are already hooked up to natural gas supplies by pipeline or have propane tanks on the property.

However, this paper discusses methanol reforming because methane has a higher energy density and is easier to transport. The process starts with the vaporization of liquid methanol and water. Heat produced in the reforming process is used to accomplish this. This mixture is passed through a heated chamber that contains a catalyst. As the methanol molecules hit the catalyst, they split into carbon monoxide (CO) and hydrogen gas (H₂). The water vapor splits into hydrogen gas and oxygen; this oxygen combines with the CO to form CO₂. It is important to eliminate as much of the CO from the exhaust gas, and this way, very little CO is released, as most of it is converted to CO₂.

B. DC/DC Convertor

Most models for fuel cells usually neglect the effect of DC/DC converters [13]. We propose in this paper the state space model and transfer functions for the combination of PEM fuel cell and related DC/DC Converter. The DC/DC converter developed was designed using the small signal state space model for the boost DC/DC Converter evolved from [14]. The introduced model is a multivariable one with two inputs and outputs, as in fig. 3.

Figure 3. Boost DC/DC converter

This convertor contains one control signal which is used to shape the duty cycle. The traditional PWM to calculate the duty cycle is not needed in this model because of a feedback loop used to calculate the duty cycle.

C. DC/AC Inverter

For larger power applications of a fuel cell the output of a generator would need to be connected to an AC load. In order to do this an inverter is needed. Several studies [15], [16]-[18] have shown that the switching function concept is a powerful tool in understanding and optimizing the performance of the inverter. Using the switching function concept, the power conversion circuits can be modeled according to their functions rather than circuit topologies. Therefore, it can achieve simplification of the overall power conversion functions. The inverter can be modeled as a black box with the input and output ports. The dc and ac variables can be input and output according to the operation mode. Then a transfer function is developed to describe the task to be performed by the circuits. In this paper, the sinusoidal PWM (SPWM) technique is considered as a control strategy. Based on the SPWM (fig. 4.), two switching functions are required for a Voltage Source Inverter (VSI).

Figure 4. (a) Carrier and control signals (b) Switching function 1 {SF₁} (c) Switching function 2 {SF₂}

D. Fuel Cell Generator and VSI with Controllers

The main function of a fuel cell and VSI controller will be to sense a load demand and provide a feedback current for fuel cell reformer to determine how much hydrogen to send forward to the fuel cell stack. This is a feedback loop that has to be completed for the fuel cell to know how much power to put out into the power system. The VSI controller mainly controls the output voltage based on the fuel cell controller (controls the stack current based on the load) in an outer loop manner. In this work, we introduce two main controllers, one based on VSI and the other for fuel cell. The controllers interact with each other and perform smart functions for the proposed DG based micro grid. The purpose of these controllers is to use it as a load following options in the presence of using this micro grid in a hybrid mode.

This paper is organized as follows: Section III presents the mathematical formulations used to create the model. Section IV presents the simulation results that were obtained using MATLAB[®] and Simulink[®], Section V illustrates the use of fuel cell generator as a micro grid and Section VI concludes the paper.

III. MATHEMATICAL FORMULATION

A. Fuel Cell Generator

The fuel cell system is continuously consuming hydrogen and the reformer is continuously generating hydrogen according to power demand. To model a reformer a second-order transfer function as in (1) is developed.

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

Controlling the hydrogen flow rate, according to power demand, is essential to the operation of a fuel cell system. A Proportional Integral (PI) controller is introduced to the system to control the hydrogen, oxygen, and water vapor flow rates. This feedback control is designed by taking the fuel cell output current and feeding it back to the input while converting the hydrogen into molar form based on (2)-(12):

The relationship between the hydrogen flow and the feedback current can be represented as

$$q_{H_2} = \frac{N_o I}{2FU} \quad (2)$$

The proposed PI controller is used to calculate the amount of hydrogen needed from the reformer which is used to determine the methane flow rate into the reformer. This can be expressed as:

$$q_{methanol} = (k_3 + \frac{k_3}{\tau_3 s}) \left(\frac{N_o I}{2FU} - q_{H_2} + q_{methref} \right) \quad (3)$$

Mathematical representation of the oxygen flow rate can be seen below:

$$q_{O_2} = \frac{1}{\tau_{H-O}} \quad (4)$$

In this model, dependence on the partial pressures of hydrogen, oxygen, and water vapor is introduced for the fuel cell stack. Some additional parameters are also used to get the model highly accurate and nonlinear. Following assumptions are made for the development of the model:

1. The operating fuel cell temperature will remain under 373 K.
2. The reaction product entering the reformer is in the liquid phase.
3. The fuel cell stack output voltage can be obtained by lumping together the individual cell parameters to represent a fuel cell stack
4. In the fuel cell and the gas flow channels the pressures are kept constant.
5. Both the hydrogen and oxidants are humidified to prevent damage to the proton exchange membrane.

According to assumptions 3 and 4, the fuel cell output voltage can be obtained by the sum of the Nernst voltage, the activation over voltage, the ohmic over voltage and the

concentration over voltage. The mathematical representation of this detailed model is as shown in (5)-(9):

$$V_{cell} = E - V_{act} - V_{ohm} - V_{conc} \quad (5)$$

where,

$$V_{conc} = \frac{RT}{zF} \ln \left(1 - \frac{I}{I_{limit}} \right) \quad (6)$$

$$V_{ohm} = I(R_{ohm0} + k_{RI}I - k_{RT}T) \quad (7)$$

$$V_{act} = -B \ln(CI) \quad (8)$$

$$E = E_o + \frac{RT}{2F} \ln[p_{H_2}(p_{O_2})^{0.5}] - E_d \quad (9)$$

To calculate E properly, E_d is used which is the reversible voltage delay. This delay is considered because of the time delay of the fuel and oxidant. Under steady state conditions, E_d is equal to zero due to the fact that the fuel and oxidants are in steady state. Also, notable in the equation above are the partial pressures of hydrogen and oxidants. These are used to help account for the delay of the hydrogen and oxidants. The three mathematical representation of this delay can be seen below:

$$E_d = \lambda_e I \left(\frac{\tau_e s}{\tau_e s + 1} \right) \quad (10)$$

$$p_{H_2} = \frac{I}{k_{H_2}} \left(\frac{\tau_{H_2} s}{\tau_{H_2} s + 1} \right) \quad (11)$$

$$p_{O_2} = \frac{I}{k_{O_2}} \left(\frac{\tau_{O_2} s}{\tau_{O_2} s + 1} \right) \quad (12)$$

B. DC/DC Converter

As discussed, the small signal state space model of the boost DC/DC converter can be obtained by using the following equations.

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-(1-D)}{L} \\ \frac{1-D}{C} & \frac{-1}{RC} \end{bmatrix} * \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{v_C}{L} \\ \frac{-i_L}{C} \end{bmatrix} * U \quad (13)$$

When solved for current and voltage in the frequency domain, results are as follows:

$$i_L = \left(\frac{-v_C(1-D)}{L} + \frac{v_C}{L} U \right) \frac{1}{s} \quad (14)$$

$$v_C = \left(\frac{i_L(1-D)}{C} - \frac{v_C}{RC} - \frac{i_L}{C} U \right) \frac{1}{s} \quad (15)$$

Additionally switching losses and input port series resistance were incorporated in this model. The output current and voltage is calculated based on [13] in order to show the switching current losses and the input port series resistance voltage losses for the converter.

$$v_O = v_C - v_{RL} \quad (16)$$

$$i_O = \frac{V_{cell}(1-D)}{R_L} - \frac{v_O(1-D)^2}{R_L} - I_{sw} \quad (17)$$

A varying duty cycle is used in this model to ensure that the output is constant. To ensure that the model was achieving a high efficiency, an algorithm for calculating efficiency with a varying duty cycle is used [16].

$$Eff = \frac{1}{1 + \frac{R_L}{(1-D)^2} \frac{i_O}{v_O}} \quad (18)$$

To achieve higher efficiency, the capacitor and inductor values are calculated using the following equation.

$$L = \frac{I_{ref}}{2fI_{Omax}} D_{max} (1-D)^2 \quad (19)$$

$$C = \frac{I_{ref} D_{max}}{f V_{ripple}} \quad (20)$$

Where,

$$D_{max} = 1 - \frac{V_{max}}{V_{ref}} \quad (21)$$

Using these equations to find the appropriate inductor and capacitor values is critical in building a boost converter that is both functional and efficient.

C. Three Phase Inverter

A three phase DC/AC inverter with switches and diodes takes a constant DC voltage input and inverts that into three phases of AC voltage. It can be configured as in fig. 5: Two switching functions SF_1 and SF_2 are used to design S_1 - S_6 indicated in fig. 5. The switching function SF_1 expresses the V_{ao} , V_{bo} , and V_{co} and it is used to calculate the inverter line-to-line voltages (V_{ab} , V_{bc} , V_{ca}) and phase voltages (V_{an} , V_{bn} , V_{cn}). On the other hand, the switching function SF_2 designates the voltage across the switch and the load currents (I_a , I_b , I_c) are derived as ratios of voltages and respective impedances using the switching function SF_2 . Mathematical representations and are given as follows:

$$SF_1 = \sum_{n=1}^{\infty} A_n \sin(n\omega t) \quad (22)$$

$$SF_2 = B_0 + \sum_{n=1}^{\infty} B_n \sin(n\omega t) \quad (23)$$

Figure 5. Circuit configuration of a three phase voltage source inverter

Each switching function has three phases (a, b, and c) all 120 degrees apart. Using the switching function $SF_{1a,b,c}$ the V_{ao} , V_{bo} , and V_{co} can be calculated.

$$V_{ao} = \frac{V_d}{2} SF_{1a} \quad (24)$$

$$V_{bo} = \frac{V_d}{2} SF_{1b} \quad (25)$$

$$V_{co} = \frac{V_d}{2} SF_{1c} \quad (26)$$

Then the inverter line-to-line voltage can be derived as follows:

$$V_{ab} = V_{ao} - V_{bo} \quad (27)$$

$$V_{bc} = V_{bo} - V_{co} \quad (28)$$

$$V_{ca} = V_{co} - V_{ao} \quad (29)$$

In order to calculate the phase voltage V_{no} is needed as shown below:

$$V_{no} = \frac{1}{3} (V_{ao} + V_{bo} + V_{co}) \quad (30)$$

$$V_{an} = V_{ao} - V_{no} \quad (31)$$

$$V_{bn} = V_{bo} - V_{no} \quad (32)$$

$$V_{cn} = V_{co} - V_{no} \quad (33)$$

Assuming the load consists of a balanced R-L load, the load currents can be determined as a ration of the phase voltage and the respective impedance as given below:

$$I_a = \frac{V_{an}}{Z_a} = \frac{V_{an}}{R+j\omega L} \quad (34)$$

$$I_b = \frac{V_{bn}}{Z_b} = \frac{V_{bn}}{R+j\omega L} \quad (35)$$

$$I_c = \frac{V_{cn}}{Z_c} = \frac{V_{cn}}{R+j\omega L} \quad (36)$$

The switch currents are calculated by the product of the load currents with the corresponding switching function $SF_{2a,b,c}$.

$$I_{S1} = I_a * SF_{2a} \quad (37)$$

$$I_{S3} = I_b * SF_{2b} \quad (38)$$

$$I_{S5} = I_c * SF_{2c} \quad (39)$$

Using all of these equations VSI can be modeled accurately. The developed model is then tested for various loading conditions. Input in the form of P and Q are

dynamically changed and the VSI output (voltage and current) and efficiency is evaluated.

D. Fuel Cell Generator and VSI with Controllers

To meet the requirements for interconnecting a fuel cell system to a utility grid and control the real and reactive power flow between them, it is necessary to shape and control the inverter output voltage in amplitude, angle, and frequency. In this section, a PWM controller is designed for the inverter to satisfy voltage regulation as well as to achieve real and reactive power control. To this end, a d-q transformation is used to transfer a stationary (abc) system to a rotating (dq0) system. The transformation decreases the number of control variables from 3 to 2 (component 0 will be zero) if the system is balanced. The d-q signals can also be used to achieve zero tracking error control. In order to determine the error, or difference between the reference signal and the actual signal a reference voltage is needed. To calculate the reference signal a set of equations are used below.

$$V_{ref} = \frac{Z^2}{E^2} (P^2 + Q^2) + E^2 + 2PZ \cos(\theta_Z) + 2QZ \sin(\theta_Z) \quad (40)$$

$$\delta = \theta_Z - \cos^{-1} \left\{ \frac{ZP}{EV_s} + \frac{E}{V_s} \cos(\theta_Z) \right\} \quad (41)$$

Where V_{ref} and δ would then need to be transformed into dq coordinates (abc/dq), and this is done by using the matrix equation as in (42). As a part of the overall control architecture a voltage and current controller was designed. Fig. 6 illustrates the design and control topologies of a VSI inverter implementation.

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (42)$$

Figure 6. Flow diagram of a VSI controller

Once the signal passes through the voltage and current controllers it must be passed through a dq/abc transformation so the signal can be used in the SPWM. The transformation is designed based on (43). A voltage and current controller is

designed for internal control of the inverter. Fig. 7 shows the block diagram of the current and voltage controller that has been used. After the design and modeling of the inverter, the system is tested with inverter and power conditioning devices.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & \frac{1}{\sqrt{2}} \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \quad (43)$$

Figure 7. (a) Current controller block diagram (b) Voltage controller block diagram

IV. MODELING IN MATLAB[®] AND SIMULINK[®] AND SIMULATION RESULTS

A. Fuel Cell Generator

Figure 8. Detailed model of a fuel cell stack

Figure 9. Detailed model of a fuel cell reformer

The proposed models are all implemented using MATLAB[®] and Simulink[®]. A detailed model developed using

MATLAB® and Simulink® for a fuel cell generator and reformer is in fig. 8 and fig. 9. There is only one input and two outputs to the fuel cell generator and they are feedback current, DC output voltage, and hydrogen flow rate respectively. The feedback current will vary depending on the load demand and the hydrogen flow rate will vary depending on the feedback current. The voltage is a function of the feedback current, partial pressures of hydrogen and oxygen, and the over voltage potential inside the fuel cell.

The fuel cell generator model shown in these figures is then tested with step changes in the feedback current as shown in fig. 10. For this test case, the generator is assumed to be in the active mode. The results of this simulation show that as the feedback current increases fuel cell voltage decreases. The increase in current increases methane flow rate and hydrogen flow rate as well. All of which has a small time delay before reaching steady state. For the variations in P and Q, the fuel cell model responded well. The tests are then compared with the datasheet of a 1 KW active fuel cell that has been purchased. The model validation proves that the nonlinear model is accurate and can be used for further analysis of FC based micro grid and smart controller designs. Also this modeling methodology has shown improvements with respect to other models that did not use, V_{ohm} and V_{conc} in the fuel cell generator. In conclusion, this model is able to accurately simulate the transient response of a real PEM fuel cell generator.

Figure 10. Results from fuel cell generator simulation

B. DC/DC Converter and Overall Fuel Cell Generator

The next step is to integrate the power conditioning devices with the nonlinear fuel cell model. The DC/DC converter detail model uses the values as in Table 1. These values are designed for the simulation and integration with the fuel cell generator. The simulation and control strategies required to integrate the converter and fuel cell model generates these

values.

TABLE 1: CONVERTER PARAMETERS

Sym.	Parameter	Value	Unit
R_L	Input Port Resistance	0.05	Ω
I_{sw}	Switching Loss Current	0.03	A
V_o	Desired Reference Output Voltage	240	V
I_c	Desired Reference Input Current	20	A
F_s	Switching Frequency	5000	Hz
R	Resistance	4.6	Ω
P_o	Max Power Output	500	W

Fig. 11 shows a simulation results performed integrating fuel cells and DC/DC converter using a variable resistive load to test the dynamic response of the fuel cell and converter together with a purely resistive load demand.

Figure 11. Results from fuel cell generator and DC/DC converter simulation

The resulting plots show that a varying converter input voltage and current results in a constant converter output voltage. The duty cycle changes to accommodate the load demand and thus the efficiency stays high.

V. FUEL CELL GENERATOR AS A MICRO-GRID

To ensure the correct response of the micro-grid, several case studies are performed. The parameters and the values used for the VSI inverter are as shown in table 2. The objective of this case study is to discuss the FC working as a micro grid with varying load under the control of VSI inverter controller and FC controller.

TABLE 2: INVERTER PARAMETERS

Sym	Parameter	Value	Unit
F	Frequency	60	Hz
F_s	Switching Frequency	1000	Hz
V_{in}	Three-Phase Voltage	480	V
Z	Impedance	0.5	(R per unit)
L	Inductance	0.05	(L per unit)

A. Case Study

Following illustration shows a case study for a light loaded distribution grid. In this case the system will also be required to deliver reactive power to the grid to help boost the grid voltage. The study is performed with a resistive and reactive load demand, considered to be light loading for this system. The excessive reactive power can be consumed by the distribution Grid system (i.e. $Q < 0$). The inputs are constants and initially considered hard switching so some sharp oscillations before it goes to a steady state are expected (Fig. 12 and fig. 13). The results indicated that the model stabilizes with high efficiency, and accurate output voltage with changing inputs.

Figure 12. Results from light loaded DC/AC inverter simulation

Figure 13. Load impedance, Resistance, Reactance, Inductance, and Complex Power as seen by the output of the inverter.

Simulation results (fig.14 and fig.15) of this case shows that the control signals respond to the real and reactive power

demanded from the fuel cell system to the utility grid. Using the control signals the power delivered to the grid can be controlled as desired while the dc bus voltage is maintained well within the prescribed range. The results also show that the fuel cell system is capable of load-following and can remain stable under the occurrence of severe faults. It is noted that a two-loop inverter control scheme has an advantage over a voltage-only control scheme for the inverter on fault protection and system stability. Also fig. 14 shows the changes in the micro grid model with respect to real and reactive power of the load.

Figure 14. Fuel cell controller output feedback current

Figure 15. VSI control output feedback signal going to SPWM

Figure 16. Micro grid system parameters with change in load

Fig. 16 show the detail analysis of testing the inverter DC/DC converter and the fuel cell in the closed loop. As it is clearly visible the inverter model works well with changing

load current producing highest efficiency and nominal voltage. After testing the inverter, overall system is analyzed as discussed next.

VI. CONCLUSION

This paper illustrates the nonlinear modeling of fuel cell with power conditioning devices such as converter and inverter. The overall model will work as a fuel cell based micro-grid and can be integrated with the mega power grid. The simulation results exactly matches with the real-time results and the controllers designed shows substantial contribution in getting a steady output from the micro-grid. Currently the model and controller validations and performed with a real-life 1KW fuel cell kit.

VII. ACKNOWLEDGMENT

Authors would like to thank National Science Foundation for the partial support for this project with award # 0748238 awarded to the first author.

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