International Journal of Research and Engineering
ISSN: 2348-7860 (O) | 2348-7852 (P) | Vol. 5 No. 9 | September-October 2018 | PP. 529-534
Digital Object Identifier DOI® http://dx.doi.org/10.21276/ijre.2018.5.9.6

Modeling of Phosphorous Acid Fuel Cell in PSCAD

ORIGINAL ARTICLE

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Abstract - The renewable energy sources, such as wind, fuel cells, etc. are gaining more attention due to the increase in energy demand as well as being environmental kindly. A dynamic model of Phosphorous Acid Fuel Cell is modeled and simulated using PSCAD/EMTDC. The system consists of a fuel cell stack along with 3-phase Pulse-Width Modulator (PWM) inverter, LCL filter and step-up transformer connected to the main grid. A Real-Reactive power controller is implemented into the 3-phase PWM inverter to control and stabilize the active and reactive power flow onto the main grid. A LCL filter is connected to the inverter side, which eliminates the ultra-harmonic distortions of the frequency. The effect of the Line-Ground, Line-Line, etc. faults on the performance of the main grid's output voltage is analyzed and studied. The fuel cell is connected to the main grid and the simulation results contain the analysis at different stages of the simulation.

***Keywords*: Inverter, Phosphorous Acid Fuel Cell, PSCAD, Renewable Energy Sources, Grid.**

I. INTRODUCTION

Due to the environmental effects and utilization of energy, the energy sources like wind, solar energy and fuel cells are becoming more crucial in integration of distributed generation for stand-alone grid applications. Of all the distributed generation technologies, a fuel cell has a great ability to produce electricity as it has no geographical limitations [1]. It has many benefits like high efficiency, high power quality, low noise, fuel flexibility, low maintenance, etc. [2]. Due to its light weight and size, a fuel cell is potentially used in space shuttles. A fuel cell is an electro-chemical device, which can obtain the electricity by converting the chemical energy. In the fuel cell chemical reaction, the hydrogen and oxygen are converted into water and electrons are released in this process. A fuel cell generally contains two electrodes called as anode and cathode which are separated by electrolyte. There are various fuel cells which are categorized based on their operating temperature and electrolyte material as: Proton Exchange Membrane (PEMFC), Alkaline (AFC), Phosphoric Acid (PAFC), Solid Oxide (SOFC), Molten Carbonate (MCFC) and Direct Methanol (DMFC) Fuel Cells. A fuel cell is selected based on application to improve the fuel cell performance. The performance of a fuel cell varies depending on the temperature, gas composition, temperature, etc. Therefore, a operating point, that is, the cell operating point must be selected to satisfy the system requirement. Among all, the PAFC is an effective and prevalent fuel cell which is used for various applications.

A Phosphorous Acid Fuel Cell (PAFC) uses phosphoric acid as an electrolyte inside a container made of silicon carbon matrix with Teflon. The catalysts are made of platinum and electrodes with porous carbon. Power density of PAFC is about 0.18W/cm2 and has a power rating ranging between 200kW – 10MW. It has an efficiency of 40-45% and operates at a temperature of 150-220℃. PAFC is mostly used in the applications of stationary power generation, electric vehicles, Combined Heat & Power (CHP), Uninterrupted Power Supply (UPS), peak shaving, etc. [3,4]. A dynamic model of PAFC is implemented in MATLAB and discussed in detailed in [1].

In this paper, an improved PAFC system is modeled and connected to the grid has been implemented in PSCAD/EMTDC. The system performance is evaluated along with the insertion of 3 phase faults at the main grid and the performance of both fuel cell and main grid are analyzed.

II. MODELLING OF PAFC

Fig. 1. The simulation challenges like limited simulation behavior of new electronic devices can be resolved using Power System Computer Aided Design / Electromagnetic Transients including DC (PSCAD/EMTDC) software package developed by Manitoba HVDC Research Center. The response time of power electronic devices ranging from nanoseconds to seconds can be performed by PSCAD tool. This tool is mainly used to simulate the power systems and power electronic circuits [5]. The modeling of PAFC can be performed in both Simulink and PSCAD. Both have similar GUI capabilities and are accurate in nature. PSCAD has faster computation time and has faster import and export choices. The data in PSCAD can be exchanged between main system and subsystem without any connection between them [5].

A typical I-V characteristics of PFAC is shown below in Fig.1 [1]. The PAFC has activation, ohmic and concentration losses. The output from the fuel cell which is a DC voltage is connected to an inverter is used to convert the fuel cell DC voltage to AC voltage.

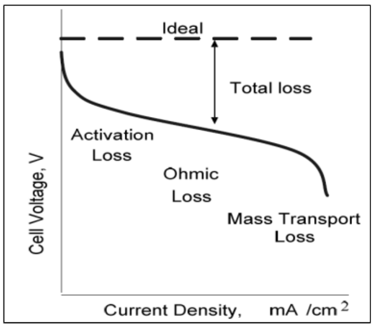

Fig. 1: Typical V-I Characteristics of a Fuel Cell

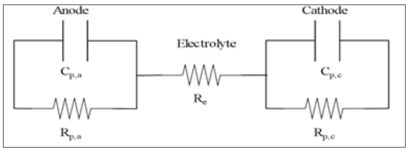

Fig. 2: Equivalent circuit of PAFC

Fig.2 represents the equivalent circuit of PAFC [6]. The equivalent circuit contains an electrolyte and electrodes. Re denotes the resistance of electrolyte in the matrix of PAFC. Electrolyte is highly conductive and the capacitive component of the electrolyte is not considered in this study. RP,a represents the anodic polarization resistance which is in parallel with the double-layer capacitance of the electrolyte and anode interface; RP,c indicates the cathode; Cdl,a and Cdl,c relates to the double-layer capacitance near the anode and cathode, respectively. Fig.3 illustrates the block diagram of individual PAFC model and is used in the development of the modeling of PAFC using PSCAD/EMTDC [7,8].

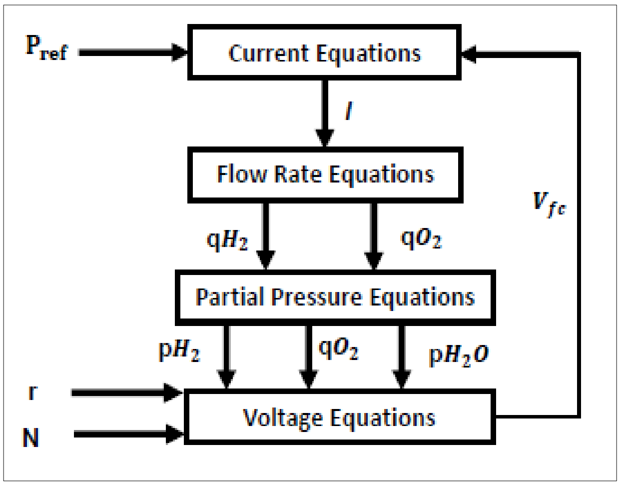

Fig. 3: Block Diagram of PAFC Model

The fuel cell stack voltage is represented by Eq.(1) as below [9]:

$$V = N_0(E_0 + \frac{RT}{2F}(ln\frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}})) - rI \qquad (1)$$

where, *V*: Total stack voltage (V), E_0: Standard reversible cell potential (V), *r*: Internal resistance of stack (Ω), *I*: Stack current (A), N_0: Number of cells in stack, *R*: Universal gas constant (J/ mol K), *T*: Stack temperature (K), *F*: Faraday's constant (C/mol), *rI*: ohmic loss of the stack.

TABLE I: PARAMETERS OF PAFC MODEL

PARAMETER	**VALUE**
Temperature	451 K
Faradays Constant, *F*	96484.56 C/mol
Universal Gas Constant, *R*	8314 J/Kmol
Standard Reversible Cell Potential, *E*	1.2V
No. of Cells	1504
Constant (*Kr = N/4F)*	0.00103
Value Molar constant for Hydrogen (KH_2)	$8.43*10^{-4}$ kmol/Satm
Oxygen (KO_2)	$2.81*10^{-4}$ kmol/Satm
Water (KH_2O)	$2.52*10^{-4}$ kmol/Satm
Response Time for Water Flow	78.3 sec
Hydrogen Flow	26.1 sec
Oxygen Flow	2.91 sec
Ohmic Loss	0.126 ohms
Electric Response Time	0.8 sec
Fuel Processor Response Time	5 sec
Ratio of H_2- O_2	1.145

Table I represents the parameters used in the modeling of PAFC [9]. Fig.4 represents the dynamic model of PAFC cell stack using PSCAD obtained from Table I and Eq. (1). Fig.5 illustrates the output voltage obtained from the PAFC fuel cell stack.

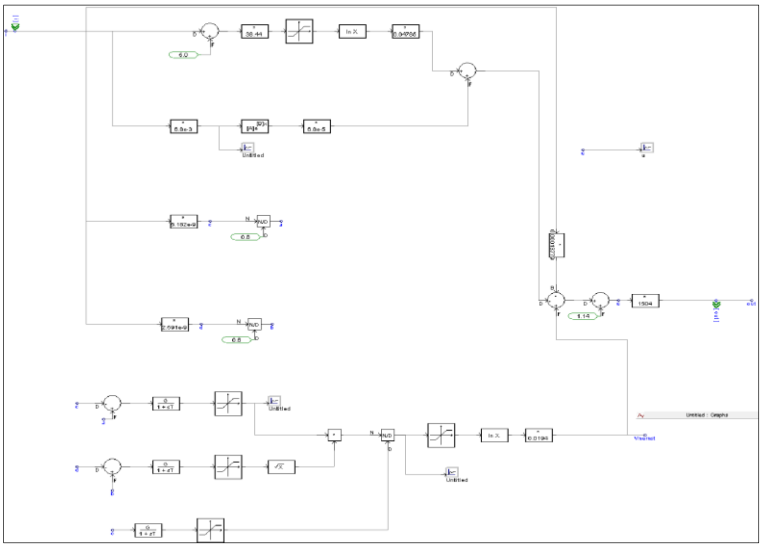

Fig. 4: PSCAD model for the fuel cell stack

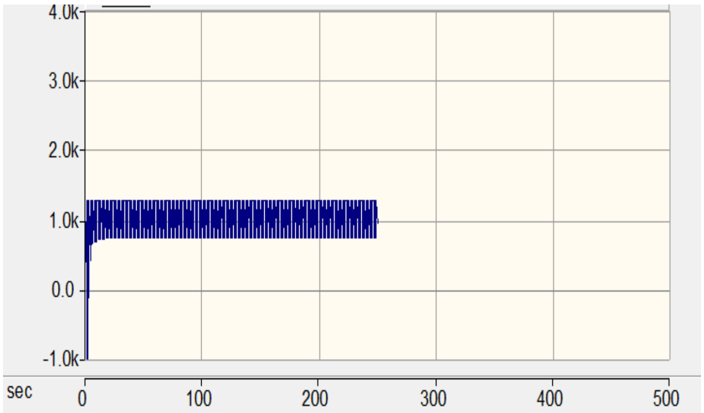

Fig 5: Output voltage of the fuel cell

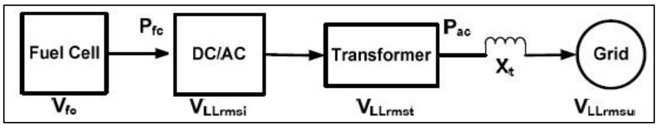

Fig. 6: Fuel cell connected to the grid

Where, V_{fc} represents the fuel cell stack voltage (V); V_{LLrmsi} denotes the output voltage of the three phase inverter (V); V_{LLrmst} indicates the voltage across the transformer (kV); X_t denotes the leakage reactance of the transformer (Ω); V_{LLrmsu} indicates the utility grid voltage (kV); P_{fc} denotes the fuel cell stack power (kW); P_o represents the output power of the DC-DC converter (kW); P_{ac} is the real power injection into the grid (kW).

A. *3-Phase PWM Inverter*

A 3-phase six switch PWM inverter is used to convert the DC voltage of the fuel cell to the AC output voltage. The inverter connects the PAFC fuel cell to the utility grid. Fig.7 represents the PWM control of the inverter [10]. Fig.8 shows the firing signals of the inverter [10].

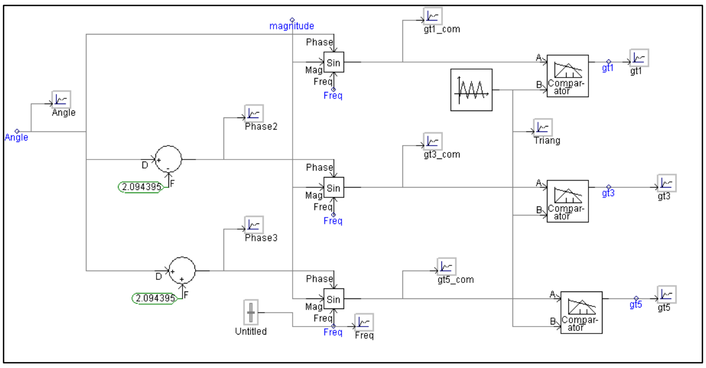

Fig. 7: Control system of PWM Inverter

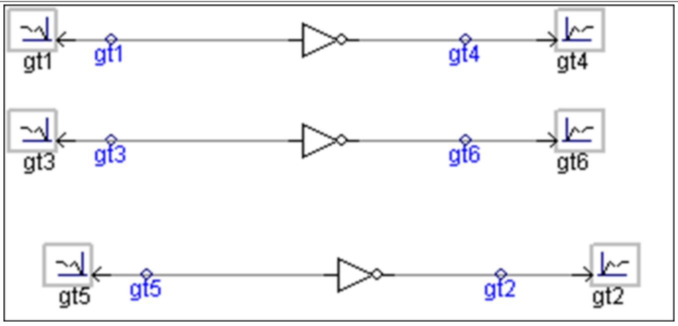

Fig. 8: Firing Gate Signals of PWM Inverter

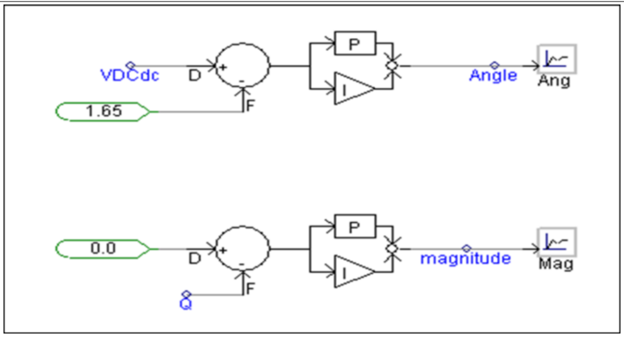

Fig. 9: Simple PQ controller

III. SYSTEM MODEL

The individual fuel cell modelling is performed in PSCAD is shown in the Fig.6 [10]. The fuel cell is connected to the main grid using the power electronic devices like 3-Phase PWM inverter, step-up transformer, LCL filter.

The phase angle and the modulation index are the main components are necessary for the inverter control. The PQ controller controls the phase angle and the amplitude of the inverter as shown in Fig.9 [11,12]. A LCL filter is connected across the inverter to filter the harmonics in the output voltage as shown in Fig.10. L = 100mH and C = 100µF is used in the LCL filter.

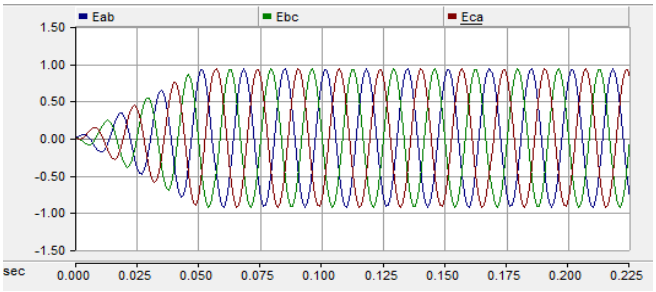

Fig. 10: Harmonics across LCL filter

A 3-phase Delta/Star - 2 winding step-up transformer of 0.66kV/12.47KV, 1MVA power rating connects the LCL filter to the main grid. The main grid is rated at 12.47 KV. Fig. 11 shows the fuel cell model connected to the 3 phase PWM inverter and Fig. 12 shows the three phase inverter-utility grid connection model in PSCAD.

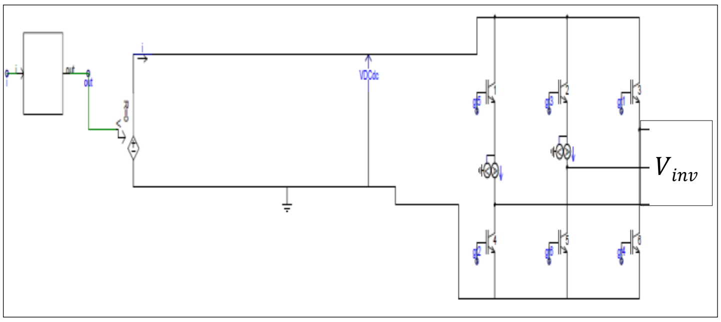

Fig. 11: Fuel cell connected to the 3-phase PWM inverter

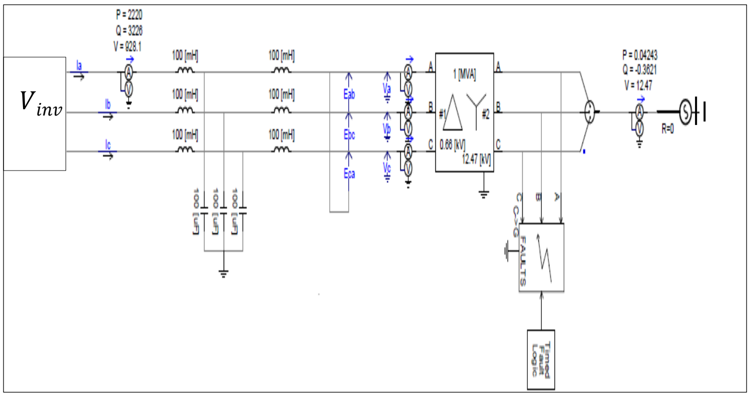

Fig. 12: output voltage from the 3 phase inverter connected to the main grid

B. Faults

The fuel cell is connected to the main grid and the simulation results contain the analysis at different stages of the simulation. The faults like 3-phase, Line to Ground (LG), Line – Line – Ground (LLG), Line – Line (LL), 3 - Line – Ground (3LG) and 3 - Line (LLL) faults are inserted across the main grid as shown below in Fig. 13-18. In Fig.13, the 3-phase fault is inserted across the main grid. At 0.5 seconds, LG fault is inserted across the main grid as shown in Fig. 14 and illustrates that line voltages A and B are obtained. At 10 seconds, LLG fault is inserted across the main grid as shown in Fig. 15 and line voltage A is obtained. In Fig 16, LL fault is inserted across the main grid at 10 seconds and the line voltage C is obtained. In Fig.17, LLLG fault is inserted across the main grid at 10 seconds. In Fig.18, LLL fault is inserted across the main grid at 10 seconds. The effects of the all the faults on the performance of the main grid's output voltage is analyzed and studied.

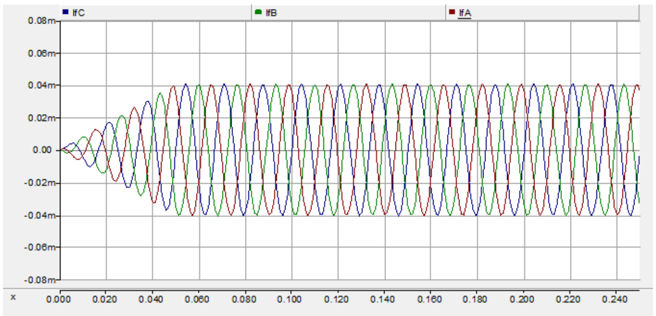

Fig. 13: 3 - phase fault

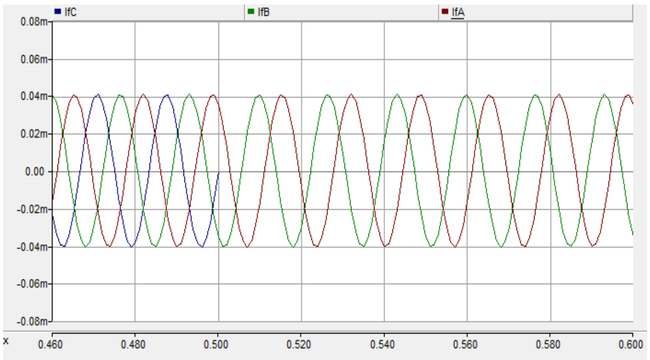

Fig. 14: At 0.5 seconds LG fault

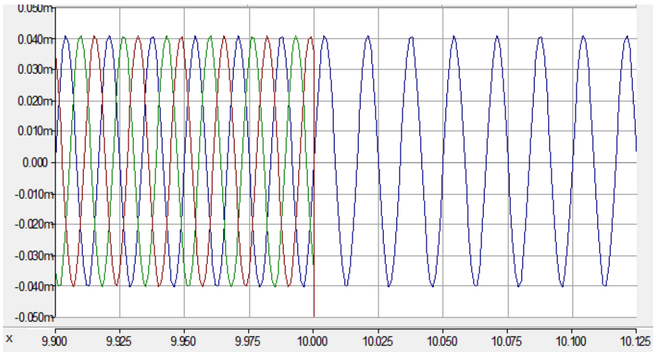

Fig. 16: At 10 seconds LL fault

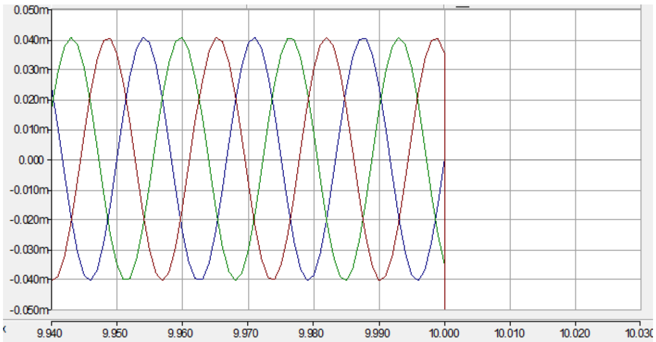

Fig. 17: At 10 seconds LLLG fault

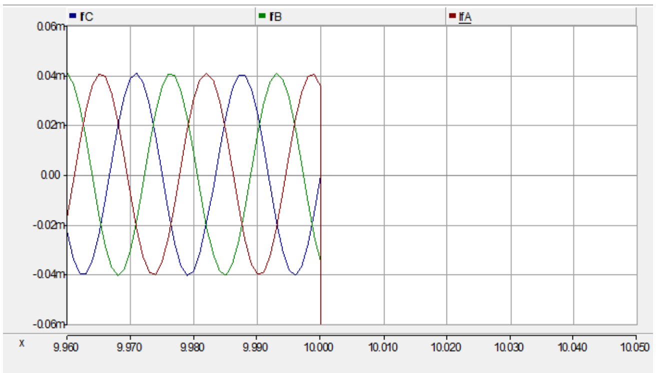

Fig. 18: At 10 seconds LLL fault

IV. CONCLUSION

An improved dynamic model of PAFC is modeled and simulated using PSCAD/EMTDC. The system consists of a fuel cell stack along with 3-phase Pulse-width Modulator (PWM) inverter, LCL filter and step-up transformer connected to the main grid. A PQ controller is implemented into the 3-phase PWM inverter to control and stabilize the active and reactive power flow onto the main grid. An LCL filter is connected to the inverter and to the main grid which reduces the harmonic distortions of the frequency. The main grid performance is analyzed by inserting the faults. The faults like 3-phase, Line to Ground (LG), Line – Line – Ground (LLG), Line – Line (LL), 3 - Line – Ground (3LG) and 3 - Line (LLL) faults are inserted across the main grid and analyzed at various stages of simulation. Thus, this paper provides an improved dynamic mode of PAFC and analyzes the operation of fuel cell and main grid by inserting the faults. The future research involves the implementation and study of droop control of 3-phase PWM inverter in the PAFC by connecting to the main grid. Also, study of PAFC connected to the weak and strong grids can be implemented.

V. DECLARATION

All author(s) have disclosed no conflicts of interest.

VI. FUNDING

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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