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Simulink simulation of solid fuel oxide cell based power generation with Efficiency Improvement

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Abstract- Solid oxide fuel cells (SOFCs) have been considered as one of the most promising technologies for very high-efficiency electric energy generation from natural gas, both with simple fuel cell plants and with integrated gas turbine/steam turbine–fuel cell systems. The high temperature exhaust gas from SOFC can be utilized in other cycles i.e. Rankine, Brayton for additional power generation or for heating and cooling purpose (cogeneration/trigeneration). The analysis shows that the resulting maximum efficiency of this SOFC-combined system can be up to 95-98% depending upon the operating condition and configuration used. This paper reviews the application of SOFC technology in power generation sector. This paper also investigate the research work undertaken or going on in this field.

Keywords:- SOFC, Cogeneration, Trigeneration.

I. INTRODUCTION

Solid oxide fuel cells (SOFCs), based on an oxide ion conducting electrolyte, offer a clean, low-pollution technology to electrochemically generate electricity at high efficiencies. Among all designs of SOFCs, the most progress has been achieved with the tubular design.

- A 100 kW power generation system utilizing tubular SOFCs, fabricated by Siemens Westing house Power Corporation, operated very successfully for over two years without any detectable performance change, and a similar 250 kW size system recently started operation. However, the electrical resistance of tubular design cells is high, and specific power output (W/cm2) and volumetric power density (W/cm3) low.

- These low power densities make tubular SOFCs suitable only for stationary power generation and are unattractive for mobile applications. Planar SOFCs, in contrast, are capable of achieving very high power densities.

- Additionally, sizeable cost reductions are possible through a concept called "mass customization" that is being pursued in the U.S. Department of Energy's Solid State Energy Conversion Alliance (SECA).

- This concept involves the development of a 3 to 10 kW size core SOFC module, that can be mass produced and then combined for different size applications in stationary power generation, transportation, and military market sectors, thus eliminating the need to produce custom-designed and inherently more expensive fuel cell stacks to meet a specific power rating.

II. RESEARCH MOTIVATION

The literature also reports studies relative to NH3-SOFC system analysis. Design studies here reported refer to different types of SOFC technologies and of power plants. This short review focuses mainly on the integration solutions presented in terms of balance of plant design. In [1] two different schemes are presented, each one integrates two heat exchangers, for both air and fuel pre-heat, and the after burner. The two designs differ from what concerns the air management strategy: required air can be fed directly to the stack, first design, or separated in two streams, bringing to a two-stacks strategy, second design. In the second design the separated amount of air is mixed to first stack cathodic off-gases and fed to the cathode of the second stack. This design allows both to reduce the temperature of the mixture and to increase oxygen concentration of the second stack cathodic inlet. As a result, the cathodic heat exchanger size is halved.

In [2] a portable system is studied. The after burner supplies the heat to a single heat exchanger that increases air temperature to stack inlet and, at the same time, supplies heat for the decomposition of ammonia. Water is also evaporated in the heat exchanger and added to the anode inlet gas mix. The model calculates up to 41.1% of efficiency for a fuel use of 0.8.

A similar design is presented in [3] but implementing a three heat exchangers solution. Two separate heat exchangers operating at high temperature recover heat separately for air and fuel. The two separated gas flows are mixed at lower temperature in an after burner that completes the oxidation of the fuel and provides hot exhausts to feed a single heat exchanger. Such a component is designed for low temperature pre-heating of both anodic and cathodic gas flows. The study shows the advantages in terms of air flow reduction due to internal ammonia decomposition reaction. A system efficiency of 50% is calculated.

In [4] a combined heat and power (CHP) system based on a SOFC-H and fed with ammonia is considered for vehicular applications. The hot gases from SOFC exhausts are mixed and split in two different gas flows to preheat ammonia and air inlet flows. The study focuses on energy and exergy analysis when varying operating parameters such as fuel use, current density, and stack temperature. The maximum efficiency of 48% is calculated when the SOFC-H operates at low current density.

III. PREVIOUS WORK

Arsalis developed a detailed thermodynamic, kinetic, geometric, and cost model analyzing the design and off design operations of hybrid SOFC–GT–ST systems ranging in size from 1.5 to 10 MW. Four different steam turbine cycles viz.

- A single pressure,
- A dual-pressure,
- A triple pressure, and
- A triple pressure with reheat

Were considered. In the thermo-economic analysis, cost functions of different system and component sizes (capacities) were included and analyzed.

Finally, the most viable system was obtained through parametric study based on maximizing total system efficiency/minimizing total system life cycle cost.

At maximum efficiency of 60.32%, the SOFC, GT and ST power output were shown to be 7.856 MW, 2.310 MW and 1.548 MW respectively. It was observed that the amount of power produced by the GT and ST plant is quite less compared to the SOFC power.

Arsalis compressed air preheating and partial fuel reforming in the PR was done by utilizing the heat of combustion gases through anode gas recycling. The combustion gases and the by-passed air stream were mixed and then it was fed into the HRSG for steam generation. There was provision for both fuel and air by-passing the SOFC. A certain amount of fuel was routed directly to the CC by-passing the SOFC. However, there was no provision for fuel preheating in his configuration although fuel preheating is one of the many techniques that can be used for achieving higher efficiency [4].

In his configuration [5] however, a multiple-pressure level (dual pressure/triple pressure with reheat) was used in order to achieve higher power output from the ST plant. Although four different ST cycles were considered in the work by Arsalis [3], but in the results and analysis, it was not clearly explained as to how these bottoming ST cycles (single pressure/dual pressure/triple pressure reheat) affected the power output of the ST cycles or the performance of the overall SOFC–GT–ST system. In so far as optimization study with SOFC–GT–ST system is concerned,

Aminyavari et al. performed multi-objective optimization study for an internal reforming SOFC–GT system integrated with a Rankine (steam) considering the exergetic efficiency and the total plant cost as conflicting objectives. A set of optimal solutions (Pareto front) was obtained and the final optimal design parameters were selected by using the TOPSIS decision-making method.

Daniel et al (2015) from University of Maryland, college park, has analyzed hybrid systems of SOFC's integrated with gas turbine engines. They have integrated SOFC's with three different gas turbine engine types' turbojet, combined exhaust turbofan and separate exhaust turbofan. Catalytic partial oxidation is used to produce fuel (hydrogen) for the SOFC.

Thermodynamic analysis is carried out for CPOx reactors, SOFC and three gas turbines resulting in increased fuel efficiencies by 4% and 8% for 50kW and 90kW respectively hybrid power systems involving SOFC/separate exhaust turbofan respectively. Similar results were shown for other gas turbine types. A parametric study on these hybrid systems show that the systems performance is dependent on operating fuel cell voltage, percent fuel oxidation, and SOFC assembly air flow. With these hybrid systems, fuel flow is reduced by 5% and electric power output is increased by ~500% without effecting TIT.

Zahar Hajabdollahi and Pei-Fang (2016) from Huazhong University of science and technology, Wuhan, China have worked on optimization of a cogeneration plant including gas turbine, SOFC, heat recovery steam generator(HSRG) as well as inlet cooling system. Individual mathematical models of each component were verified with the experiment data from literature and results were observed to be in ~2% range. A probability is carried by varying a system's design parameters like compressor & turbine efficiencies, Turbine inlet temperatures(TIT), fuel mass flow rate etc,. This study resulted in 5 optimum design points A-E. Point A shows maximum exergy efficiency of 0.4849 and worst total cost rate (TCR) i.e 1044$/hr, whereas point E shows minimum TCR (734$/hr) with a lower exergy efficiency of 0.4590. Remaining points shows moderate values of both objectives. Design points A and B include SOFC where other points do not include it. Thus, adding a SOFC system to the gas turbines increases exergy efficiencies where the TCR grows worst.

Barelli et al (2016) from University of Perugia, Perugia, Italy worked on SOFC/ GT system integrated in Micro- Grids. They stated that SOFC/GT hybrid system efficiency performance increases with a mean efficiency of 54.5% on daily basis and its short time response and a wide load perturbations as low as 42.8% of hybrid systems full power. In their research work, SOFC-GT hybrid systems dynamic model is created with control strategy to regulate the SOFC and GT systems to the load demand with safe SOFC operation. With drop in load demand, SOFC's efficiencies increases slightly by 2% for a load drop from 95kW to 62.5kW. This shows that SOFC-GT hybrid system with a wellestablished control strategy is one of the efficient power generation system for high load demand fluctuations.

Penyarat (2015) from King Mongkut's University of Technology North Bangkok, Thailand have worked on two different configurations of the SOFC-GT hybrid systems. For one of the configuration, fuel exchanger's hot stream is drawn from combustor and other from turbine exit. First configuration results in higher SOFC operating temperature and lower Turbine inlet temperature vice versa for the second configuration. First hybrid system's overall efficiencies are ~4.5% higher than second one. This is due to the higher operating temperature of SOFC system where as GT efficiency is higher in second configuration.

McLarty et al (2013) from University of California worked on integration of fuel cells with gas turbines. They have come up with molten carbon fuel cell and SOFC hybrid systems with Gas turbines. Steady state models for each hybrid systems are created and analyzed. Both the hybrid systems are assumed with cathode recirculation to increase the inlet air temperatures. These hybrid systems can produce up-to 1.2 MW electric power with LHV efficiencies higher than 70% and 75% respectively. This study shows that SOFC-GT hybrid systems are more efficient in terms of fuel LHV. McLarty et al also worked on dynamic models of the hybrid systems with additional control methods.

Massardo & Lubelli (1999) developed four different hybrid cycle configurations of SOFC's plus internal reforming integrated with gas turbines. Numerical thermodynamic models were modeled to understand the impact of anode and cathode inlet temperatures on thermos cycles.

Campanari & Iora (2004) analyzed hybrid cycle of micro gas turbine integrated with SOFC. Hybrid cycles analysis results showed an overall electrical energy efficiency increased to 63% and when SOFC is used as CHP system, thermal efficiency increased to 86%. A similar study by Haseli (2008) on SOFC hybrid cycles, with on additional air and fuel recuperates increased energy and exergy efficiencies to 60.6% and 57.9% respectively.

Mehrpooya et al (2014) compared cross and co-flow planar SOFC hybrid systems and observed that both the configuration delivered similar results. A further parametric analysis of the model resulted in increase in power output with inlet temperature and pressure of SOFC stack.

IV. PROPOSED METHODOLOGY

Today, new advances in power generation technologies and new environmental regulations encourage a significant increase of distributed generation resources around the world. Distributed generation systems (DGS) have mainly been used as a standby power source for critical businesses. For example, most hospitals and office buildings had stand-by diesel generators as an emergency power source for use only during outages.

However, the diesel generators were not inherently cost-effective, and produce noise and exhaust that would be objectionable on anything except for an emergency basis. On the other hand, environmental-friendly distributed generation systems such as fuel cells, micro turbines, biomass, wind turbines, hydro turbines or photovoltaic arrays can be a solution to meet both the increasing demand of electric power and environmental.

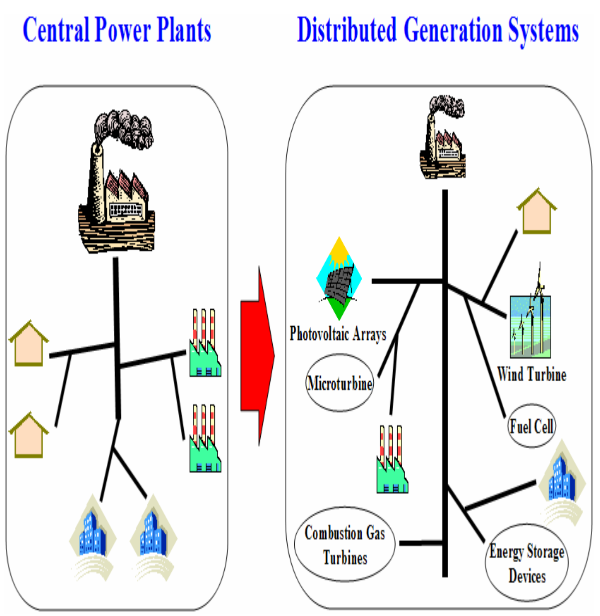

Fig 1. A large central power plant and distributed generation systems.

Regulations due to green house gas emission. Figures show future trends of electric utility industry and operating system for the DGS connected to an AC grid, respectively. As illustrated in these figures, the currently competitive DGS units will be constructed on a conventional distribution network, instead of large central power plants because the DGS can offer improved service reliability, better economics and a reduced dependence on the local utility.

Recently, the use of distributed generation systems under the 500 kW level is rapidly increasing due to technology improvements in small generators, power electronics, and energy storage devices.

Efficient clean fossil-fuels technologies such as micro-turbines, fuel cells, and environmental-friendly renewable energy technologies such as biomass, solar/photovoltaic arrays, small wind turbines and hydro turbines, are growingly used for new distributed generation systems. These DGS are applied to a standalone, a grid-interconnected, a standby, peak shavings, a cogeneration etc. and have a lot of benefits such as environmental-friendly and modular electric generation, increased reliability/ stability, high power quality, load management, fuel flexibility, uninterruptible service, cost savings, on-site generation, expandability, etc.

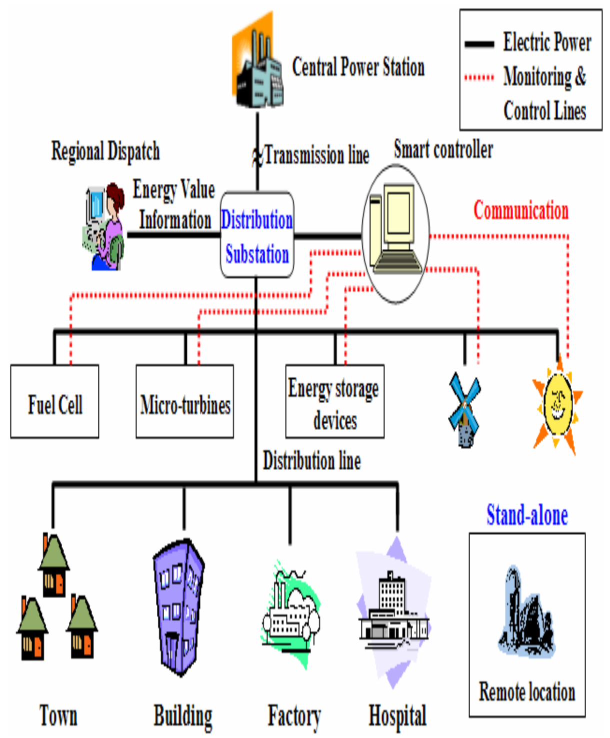

Fig 2. Operating system for DGS.

The major distributed generation technologies that will be discussed in this chapter are as follows: micro-turbines, fuel cells, wind turbines, solar/photovoltaic systems, and energy storage devices.

Other distributed energy technologies are combustion/diesel engines. However, these technologies will not be explained due to high emissions, high operation and maintenance costs.

1. Fuel Cell Plant Description:

Fuel cell produce dc power, water and heat from the combination of hydrogen produced from the fuel and oxygen from the air. In procedure where CO and CH4 react in the cell to produce hydrogen, CO2 is also a co-product.

Reactions in fuel cells depend substantially on the temperature and pressure inside the cell. A system must be built around the fuel cell to supply air and clean fuel, convert the energy to a more usable form such as grid quality ac power, and remove the depleted reactants and heat that are produced by the reactions in the cells. The block diagram representation of the SOFC dynamic model is shown in the Figure

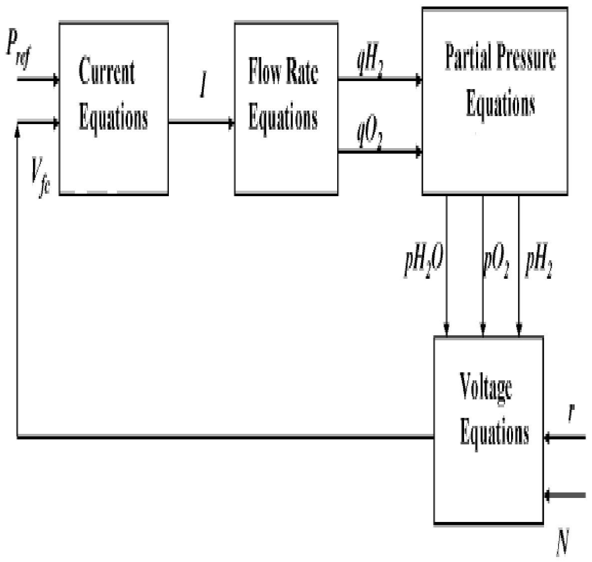

Fig 3. Fuel Cell Plant.

Fuel cells are also well used for distributed generation applications, and can essentially be described as batteries which never become discharged as long as hydrogen and oxygen are continuously provided.

The hydrogen can be supplied directly, or indirectly produced by reformer from fuels such as natural gas, alcohols, or gasoline. Each unit ranges in size from 1-250 kW or larger MW size. Even if they offer high efficiency and low emissions, today's costs are high. Phosphoric acid fuel cell is commercially available in the range of the 200 kW, while solid oxide and molten carbonate fuel cells are in a pre-commercial stage of development.

The possibility of using gasoline as a fuel for cells has resulted in a major development effort by the automotive companies. The recent research work about the fuel cells is focused towards the polymer electrolyte membrane (PEM) fuel cells. Fuel cells in sizes greater than 200 kW, hold promise beyond 2005, but residential size fuel cells are unlikely to have any significant market impact any time soon.

Figure shows a block diagram of fuel cell system which consists of a reformer, fuel cell stack and a PCU. Also, features of four types of the fuel cells appropriate for Distributed generation systems features are summarized below and overview of these types is listed in.

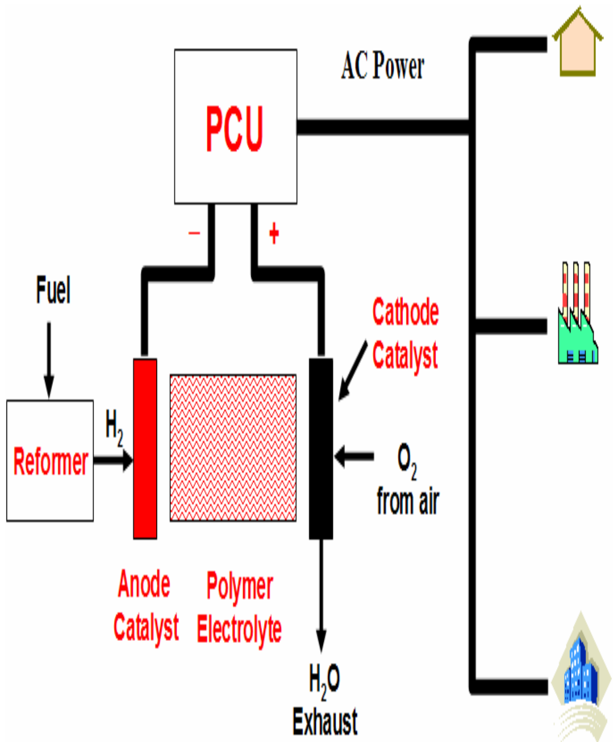

Fig 4. Block diagram of fuel cell system.

The main objective of this paper is to propose a 3-phase FC stand-alone power supply having only single energy conversion converter along with a back-up unit is shown in Figure 4.4. The cost of this proposed system is reduced by making the multi stage conversion system with a single stage system, i.e. boost-inverter due to this the switching losses and conduction losses are also reduced.

Generally, the diagram shown in Figure 4.4 shows that boost converter is followed by the Fuel Cell and the back-up energy storage system, these two converters are connected at the same bus and output from the boost inverter is a three phase AC and it is connected to three phase balanced star connected resistive load4. The Fuel Cell system has operated in current mode controlled bidirectional converter for battery converter to support the Fuel Cell.

In this proposed concept the 3-ø boost inverter is separated to three individual converters for three phase arms and connected to three individual balanced loads, as shown in Figure 4.4.

The dc-biased three phase output voltages are described by In the above equation Ao is the peak amplitude of line-to-neutral voltage and Vdc is dc voltage across each converter which is greater than Ao + Vin. In this boost converter generates ac output voltage with dc bias, so that the output voltage generated from the boost converter is greater than the input voltage from the fuel cell and have equal magnitude the dc components are canceled5.

Three-phase three-wire balanced output and the expression for line to line voltages are, A stand-alone 3-ø Fuel Cell power supply based boost converter along with a battery energy storage system has been successfully proposed. With these Simulation results the operational characteristics of FCBI has been understand. The results of the proposed 3-ø FC supply have confirmed its satisfactory performance in delivering boosting and inversion functions

in one conversion stage to generate 210 Vac at rated power. The back-up unit key function is to support the slow variations of the Fuel Cell. Finally, the efficiency of this proposed boost inverter fuel cell system is improved with its single stage conversion process and from economical point of view it is better than all other conventional converters. It is in compact size because of usage of less number of switching devices.

V. RESULT AND SIMULATION

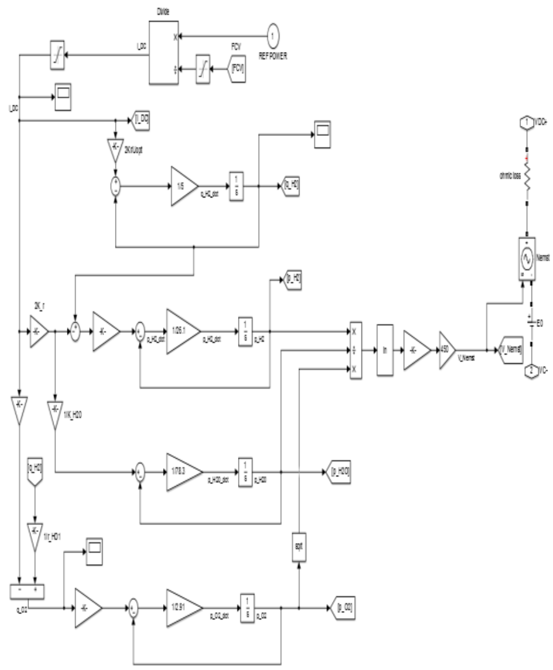

Fig 5. Simulink model.

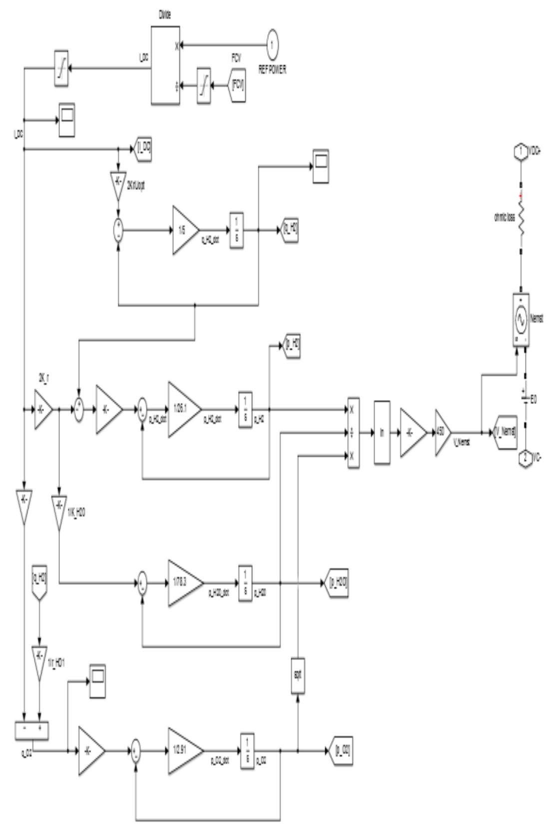

Fig 6. Subsystem of Fuel cell.

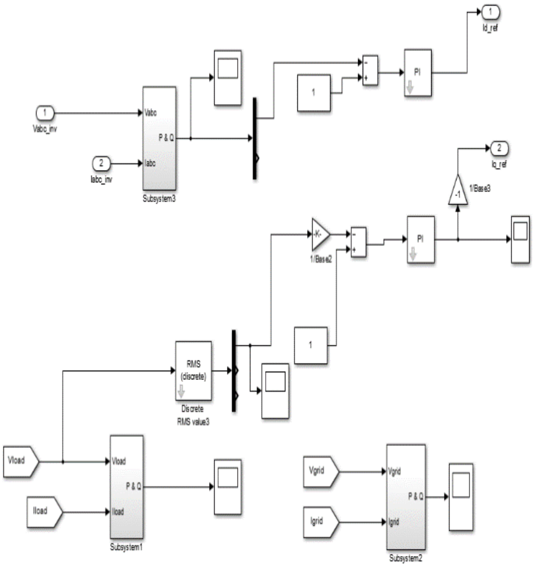

Fig 7. Power regulation Simulink block.

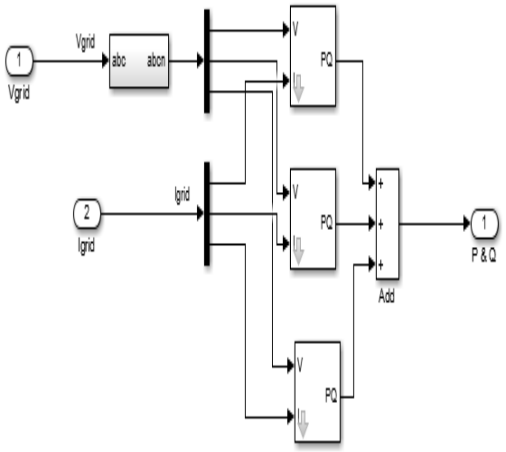

Fig 10. Power measurement calculation.

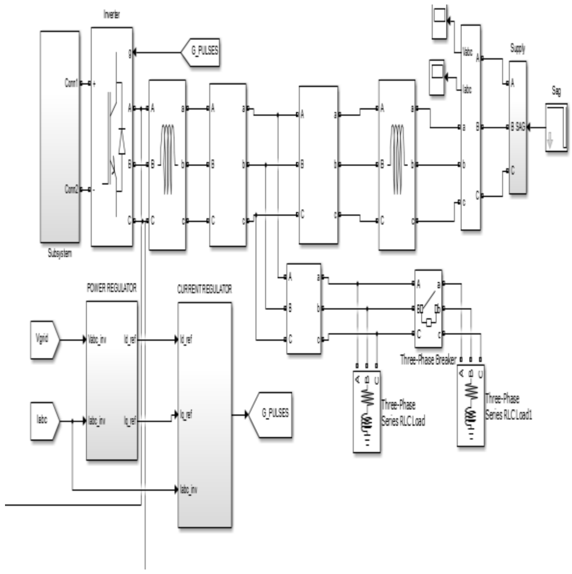

Fig 11. Grid connected system.

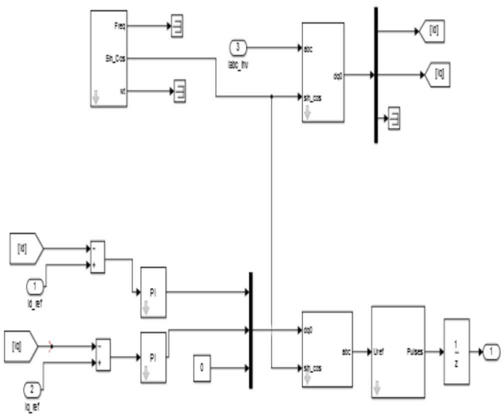

Fig 8. PI based topology.

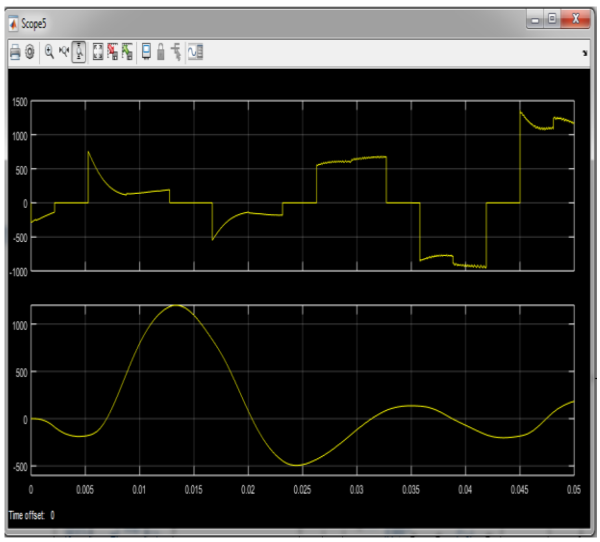

Fig 12. Topology z transformation.

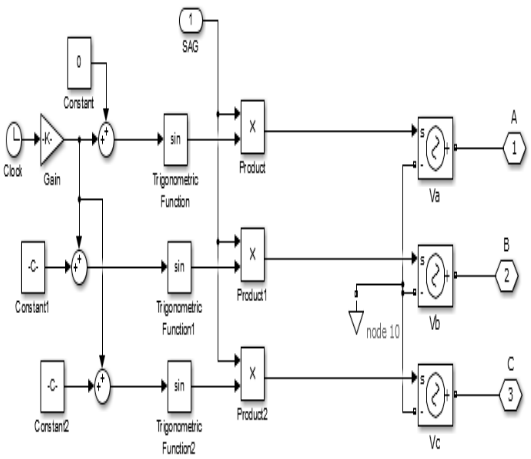

Fig 9. Power system measurement block.

Table 1. Comparison of base paper and our topology output.

S.N.	BASE PAPER MAXIMUM EFFICIECIENCY	PROPOSED TOPOLOGY BASED MAXIMUM EFFICIENCY
1.	**92%**	**95-98%**

If compared with conventional fossil fuel propelled electric generators, the use of fuel cells brings about many advantages [1]:

- Higher volumetric and gravimetric efficiency
- Low chemical, acoustic, and thermal emissions
- Modularity and siting flexibility
- Low maintenance
- Fuel flexibility (depending on type of fuel cell)
- No production of pollutants

VI. DISCUSSION AND CONCLUSIONS

This study presents the design and modeling of an ammonia-fed SOFC system based on experimental campaign on a six cells SOFC short stack. An innovative design is presented, and the relative model was implemented to calculate thermodynamic parameters.

The experimental study of operating conditions of a SOFC short stack fed with ammonia was performed. The correlation with use of fuel, current density, and ammonia decomposition was studied at an operating temperature of 750 ◦C. The external ammonia decomposition has a minimum influence on performance, meaning that internal cracking of ammonia in the stack is a feasible solution. The stack achieves up to 95-98%efficiency at 750 ◦C.

Measurements done on the ammonia emissions show NH3 content in the range 40–250 ppm when moving to the highest current densities. The system model allowed to calculate up to 95-98% of net efficiency in nominal condition. The parameter study showed how external decomposition of ammonia increases the size of the heat exchangers with no advantages in terms of efficiency. The most feasible strategy to variate system power is to rate the current density. Reduction of current density improves the efficiency of the system and increases oxygen use.

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