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Silicon Oxide Fuel Cell Energy Source Implementation in D-STATCOM Power Circuit for Power Quality Enhancement

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Abstract-
Silicon Oxide Fuel Cell (SOFC) as a non-conventional energy source is implemented for D-STATCOM power circuit. A detailed description of the SOFC modelling approach is given in this paper. This methodology is used in D-STATCOM power circuit for an energy source. A SOFC Based D-STATCOM is implemented to mitigate various symmetrical as well as unsymmetrical fault conditions. Advantages and disadvantages for implementation of SOFC are also discussed.

Keywords: *D-STATCOM, Fault, SOFC, PQ*

I. Introduction:

Power supply is generated by conventional and non-conventional methods. DC energy storage unit is main parts of D-STATCOM power circuits. Various Devices like super capacitors, SMES, Flywheels, batteries, Solar cell and are used as in D-STATCOM power circuits as an energy storage devices. These energy sources are derived from conventional sources. The real power requirements of the system are supplied by D-STATCOM when it is in the injected mode during the voltage sag compensation [1-5].

The advantages of uses of renewable energy sources are that these types of sources are unpolluted and unlimited. The uses of renewable energy sources have capability to reduce the air pollution and greenhouse gas emissions. It has the drawbacks high initial setup cost but in remote area or rural village it very well may be an economy arrangement in correlation with another arrangement of electrical system.When the renewable energy source systems are connected to the electrical network it provided the efficiency and reliability[6-8].

Fuel cells as a non-conventional energy source it has capability to supply the instantaneously electrical power as per the system requirement. It is supply the energy without air pollution and creation them appropriate for a hybrid zero emission distribution and transmission electric network. Fuel cells have a more safe operation as compared to traditional sources of variouscategorieslike liquid and dry batteries. In the D-STATCOM power supply module fuel cell we can use in combined multiple stack forms to fulfil the system requirement.

To fulfil the instantaneously electrical power a capacitor bank is additional added to the D-STATCOM circuit and it supply the instant requirement of the system.

The aim of this paper is to explore the operation to replace conventional DC energy storage for D-STATCOM power circuit with a new non-conventional energy source. A SOFC as a new energy storage is suggested for D-STATCOM power circuit and its implementations are discussed for various voltage sag compensation techniques [9-12].

II. Modelling of a SOFC System

Fuel cells are rising as one of future elective energy asset to supplant conventional energy sources. In the SOFCelectrochemical process take place and it convert chemical energy into electric energy and it produce DC voltage output. At the time of electricity generation reverse electrolysis process take place in it.

NumerousVarieties of Fuel cells are used in present time like Solid Oxide,Phosphoric Acid, Polymer Electrolyte and Molten Carbonate.

(i) Alkaline Fuel Cell (AFC) :

A SOFC fuel cell has the properties like it is environmentally friendly, modular, and capable to supply the electric power so it is attractive. A SOFCs in particular, have many advantages, including high efficiency, low cost of manufacturing and availability for on-site power generation systems with rated power between 1 kW and several MWs. It hasa drawback pollute the environment due to low emissions of the gases like SOx, $NO_x$and CO_2.

A SOFC system uses stack of cells. This cell stack has an innovative structure, achieving lower cost in mass production and high-voltage / low-current generation by using a structure where multiple cells are connected in series on a sintered ceramic substrate. SOFC working temperature is between 900-1000^oC and effectiveness of the request for 50-60%.The electrolyte right now is a strong, nonporous metal oxide and the charge transporters are oxygen particles. The electrolyte consistently stays in a strong state adding to the inalienable effortlessness of the fuel cell. The strong fired development of the cell, can limit equipment consumption, considers adaptable plan shapes, and is impenetrable to gas hybrid from one anode to the next. Because of the high temperature activity, high response rates are accomplished without the requirement for costly impetuses and furthermore gases, for example, gaseous petrol can be inside improved without the requirement for fuel changing. One of the fundamental feeble purposes of fuel cell is its moderate elements reaction. To take care of these issues, the framework must have a quick assistant source, to supply or retain high transient energy. Due to this problem a high current super capacitor topology has been developed [9-12].

Various parts of fuel cells (FC) plant:

a) **Power Conditioner:** it is used for rectification purpose i.e. DC to AC power output.
b) **Fuel Processor:**it is a device that is used to for feed hydrogen to a fuel cell
c) **Power Section:**As per the requirement of the system it combined in the stack or bundle form to generate the supply.

III. Linearized Model of SOFC

Following assumptions are considered:

(i) The gases should be idealin Fuel cell
(ii) In the interior of the electrodes pressure should be define in single
(iii) Temperature of the fuel cell should be constant at all periods
(iv) Nernst's condition ought to be pertinent

Sluggish dynamics of a solid oxide fuel cell equationas shown below;

$$\frac{dI^r_{FC}}{dt} = \frac{1}{T_e}\left[-I^r_{FC} + I_{ref}\right]$$

$$\frac{dq^{in}_{H_2}}{dt} = \frac{1}{T_F}\left[-q^{in}_{H_2} + \frac{2K_r}{U_{opt}} I^r_{fc}\right]$$

$$\frac{dP_{H_2}}{dt} = \frac{1}{\tau_{H_2}}\left[-P_{H_2} + \frac{1}{K_{H_2}}\left(q^{in}_{H_2} - 2K_r I^r_{fc}\right)\right]$$

$$\frac{dP_{H_2O}}{dt} = \frac{1}{\tau_{H_2O}}\left[-P_{H_2o} + \frac{2K_r}{K_{H_2O}} I^r_{fc}\right]$$

$$\frac{dP_{O_2}}{dt} = \frac{1}{\tau_{O_2}}\left[-P_{O_2} + \frac{1}{K_{O_2}}\left(\frac{1}{\tau_{HO}} q^{in}_{H_2} - 2K_r I^r_{fc}\right)\right]$$

$$I_{ref} = \begin{cases} q^{in}_{H_2}\dfrac{U_{\max}}{2K_r}, if \quad \tilde{I} > q^{in}_{H_2}\dfrac{U_{\max}}{2K_r} \\ q^{in}_{H_2}\dfrac{U_{\min}}{2K_r}, if \quad \tilde{I} < q^{in}_{H_2}\dfrac{U_{\min}}{2K_r} \\ \tilde{I} = \dfrac{P_{ref}}{V_{ref}}, \quad otherwise \end{cases}$$

Where Fuel cell current = I^r_{fc} *;*

Hydrogen input flow = $q^{in}_{H_2}$ *;*

Partial pressures of water, hydrogen, oxygen denote by p_{H_2O}, p_{H_2}, p_{O_2}.

The fuel cell time constants is denote by T_e, T_f, τ_{H_2}, τ_{O_2}, τ_{H_2O}

Where; K_{H_2} (hydrogen) K_{H_2O} (water)and K_{O_2} (oxygen) Valve molar constants

Optimal, maximum, and minimum fuel utilization is denoted by U_{opt}, U_{max}, and U_{min}.

Finally,

$$K_r = N_o / (4F)$$

The output of fuel cell (stack) is given by Nernst equation

$$V_{dc} = N_o[E_o + \frac{RT}{2F}\log(\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2}})] - rI^r_{fc}$$

Where

R = Ohmic loss

T= Absolute temperature

E_O= universal gas constant,

N_O= No. of fuel cells stack in series

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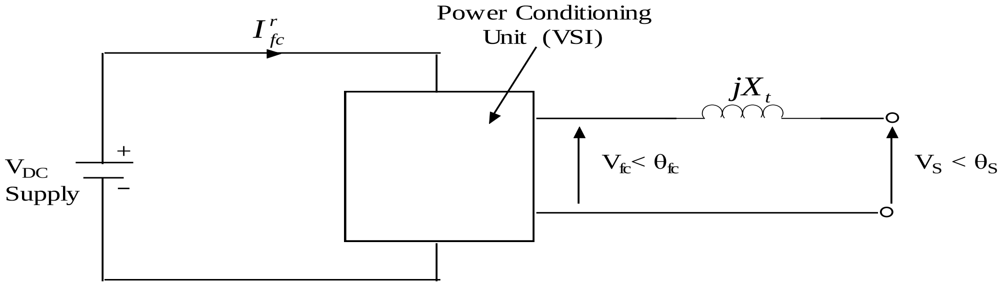

Fig.1: Schematic of a Fuel Cell-Driven Power Plant

Fig.1:Schematic of a Fuel Cell-Driven Power Plant, Voltage source inverted generated active power by fuel cell. $V_{fc}<\theta_{fc}$is represent the output of the VSI which is in the form of AC. This circuit can be used for directly to the feeder through transformer [13-16].

$$P_{fc} = \frac{k\,m V_{DC} V_s}{X_t} \sin(\theta_{fc} - \theta_s)$$

$$P_{fc} = \frac{V_{fc} V_s}{X_t} \sin(\theta_{fc} - \theta_s)$$

Constant is represented by k, which is characterized by the design of the VSI and m represents the amplitude modulation index.Fuel cell Voltage is represented by V_{fc}.

Also

$$V_{fc} = k\,m V_{DC} \,.$$

A fundamental SOFC power structure dynamic model used for execution examination during typical activity is showed up in Fig.2. SOFC parameters and their typical values used in Fig.2 have been presented in Table 1.

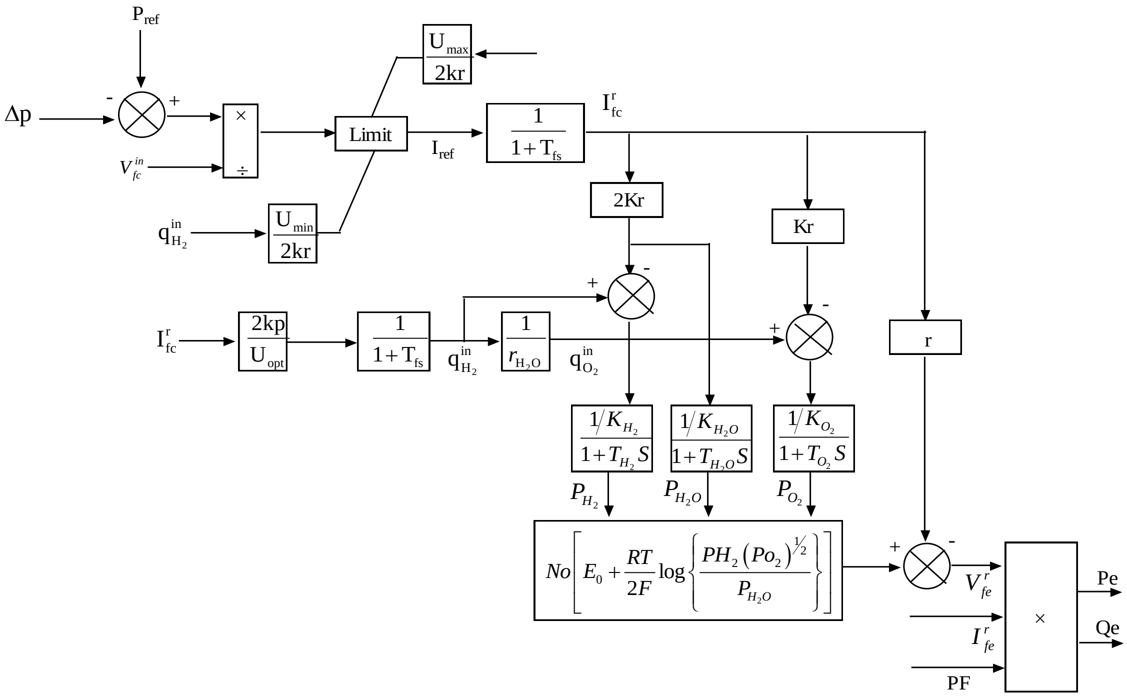

Fig.2: A SOFC System Dynamic Model

Table 1: Parameters in SOFC Model

Parameters	Item	Standards
T_e	Response Time of Electrical	0.8 s
T_f	Response Time of Fuel Processor	5 s
P_{nom}	Real Power	-
U_{opt}	Optimal Fuel Utilization	0.85
P_{ref}	Reference of Real Power	-

U_{min}	Utilization of Minimum Fuel	0.8
K_r	K_r is a Constant. It is equal to $K_r = \frac{N_o}{4F}$	0.996×10^{-6}kmol/(A-s)
K_{H2}	Hydrogen Molar Constant Value	8.43×10^{-4} kmol/(s-atm)
T	Absolute (Temperature)	1273^o K
F	Faradays (Constant)	96487 C/mol
R	Universal Gas , Constant	8314J/(kmol-^{o}K)
E_o	Ideal Standard, Potential	1.18V
N_o	Number of Cells in Series in the Stack	-
K_{H2O}	Water Molar Constant Value	2.81×10^{-4} kmol/(s-atm)
U_{max}	Fuel Utilization (Maximum)	0.9
K_{O2}	Oxygen Value Molar Constant	2.52×10^{-3} kmol/(s-atm)
T_{H2}	Hydrogen Flow Response Time	26.1s
T_{O2}	Oxygen Flow Response Time	2.91 s
T_{H2O}	Water Flow Response Time	78.3s
r_{h_o}	Ratio of Hydrogen to Oxygen	1.145

A brief procedure for SOFC implementation steps are as follows.

(a) CO is the fuel of SOFC and its reaction is

$$CO + H_2O \rightarrow CO_2 + H_2$$

H_2 and $O_2$are representing the input of the fuel cells.

(b) Fuel utilization, it is ratio of

$$U_f = \frac{q^f_{H_2}}{q^{in}_{H_2}}$$

Typically, 75-85% fuel utilization is utilized. The below equation can be written by using.

$$q^f_{H_2} = \frac{N_o I^f_{fc}}{2F} = 2K_r I^f_{fc}$$

For a specific info hydrogen flow, the demand current can be represent in the limit

$$\frac{0.8q^{in}_{H_2}}{2K_r} \le I^{in}_{fc} \le \frac{0.9q^{in}_{H_2}}{2K_r}$$

(c) The real output current in the fuel cell can be estimated

$$q^{in}_{H_2} = \frac{2K_r I^r_{fc}}{0.85}$$

(d) The electrochemical reactions occurring in SOFCs utilizing H_2 and O_2 are.

$$H_2 + O^= \rightarrow H_2O + 2e^- (\text{anode})$$

$$\frac{1}{2}O_2 + 2e \rightarrow O^= (\text{cathode})$$

The overall fuel cell reaction is

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

The hydrogen to oxygen ratio is taken in rh_O is 2 to 1. Oxygen stream is controlled to keep rh_O at 1.145 by speed control of the air blower.

(e) The substance reaction in the fuel processor is typically delayed as it is connected with an opportunity to change the compound response parameters after an adjustment in the progression of reactants. This dynamic reaction work is demonstrated as a first-request move work with a 5 s time consistent.

(f) The electrical reaction time in the fuel cells is commonly quick and principally connected with the speed at which the compound response is fit for re-establishing the charge that has been depleted by the heap. This dynamic reaction work is likewise displayed as a first-request move work yet with a 0.8 s time consistent.

(g) Through the power conditioner, the fuel cell framework can yield real power as well as reactive power. As a rule, power factor can be in the scope of 0.8-1.0. Since the reaction time of the power conditioner is under 10 ms, it isn't important to remember its point by point model for dynamic fuel cell framework aside from it is accepted that power factor can be balanced in like manner by the power conditioner.

(h)The perfect execution of SOFC is characterized by its Nernst potential spoke to as cell voltage, condition gives a connection between the perfect standard potential (E_o) for the cell response and the perfect balance potential (E) at different temperatures and fractional weights of reactants and items.

$$E = E_O + \frac{RT}{2F} \ln\left[\frac{P_{H_2}[P_{O_2}]^{\frac{1}{2}}}{P_{H_2O}}\right]$$

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IV. Important Discussions and Advantage of SOFC

Some of the advantages, cost of fuel cell, durability and bad infrastructure are explained as below[10-15].

(a) Advantages of SOFC

SOFC have following advantages

(a) It has high efficiency.
(b) SOFC has fuel flexibility.
(c) It can be utilized an assortment of catalysts.
(d) Solid electrolyte diminishes the electrolyte the board issues.
(e) It is conservative, light weight and has no moving parts. In this manner it is 99.9% dependable.
(f) It has most reduced contamination rate when contrasted with batteries just as fuel powered gadgets. In this manner, contamination is decreased by 99%.
(g) The by and large effectiveness of a fuel cell is high when contrasted with battery.
(h) The purpose behind utilizing SOFC fuel cell is that it needn't bother with produce noise, unsafe emission or contaminating gases and it is without fuel. Such a modular fuel cell framework can be immediately introduced anyplace, requires insignificant support to keep the framework running and furthermore no moving parts to wear out or separate.

(b) Cost of SOFC

SOFC is very costly because maximum cost around 75-80% is due to anode catalysts like gas diffusion layers &platinum. It can be brought down by replacing platinum with newmaterial.

(c) Durability of SOFC

It is very durable due to high temperature cell,vague long services life & long operating time

(d) Limitation of SOFC

It is required proper infrastructure for generated hydrogen transportation.

V. A SOFC based D-STATCOM Power Circuit

Three phase connection model is shown in Fig.3 &D-STATCOM based three phase power system model is shown in Fig.4. Controlling of D-STATCOM model is shown in Fig. 4(a).This system is design with an 11 kV, 50 Hz generator, feeder is connected with three phase transformer Y/Δ/Δ, 11/132/11 kV.Electrical circuit model of SOFC Based D-System parameters for this model are listed in Table 2[12-16].

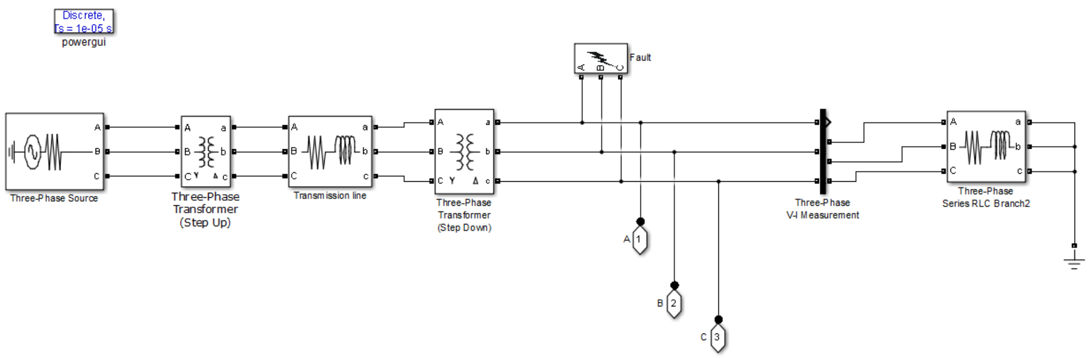

Fig. 3: Three Phase SOFC Connection Model

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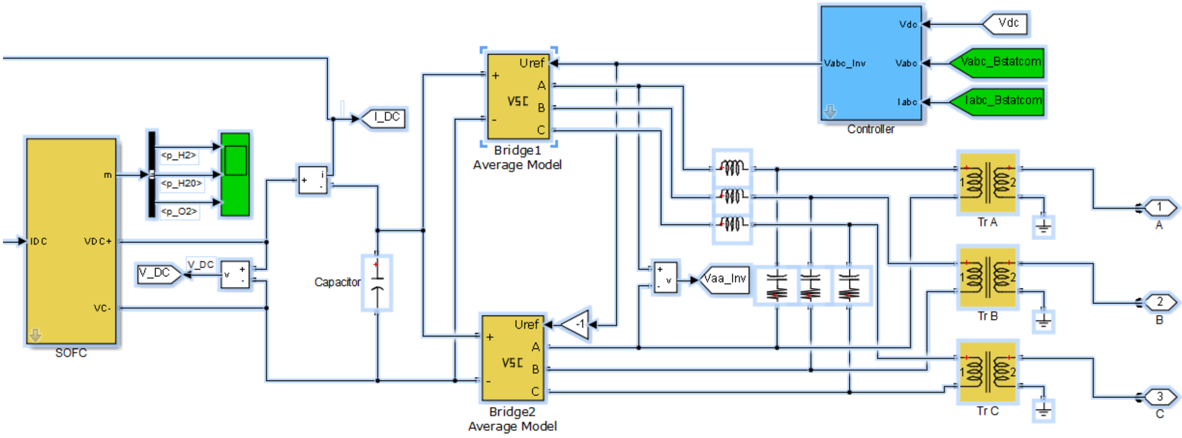

Fig.4: A SOFC Based D-STATCOM Model

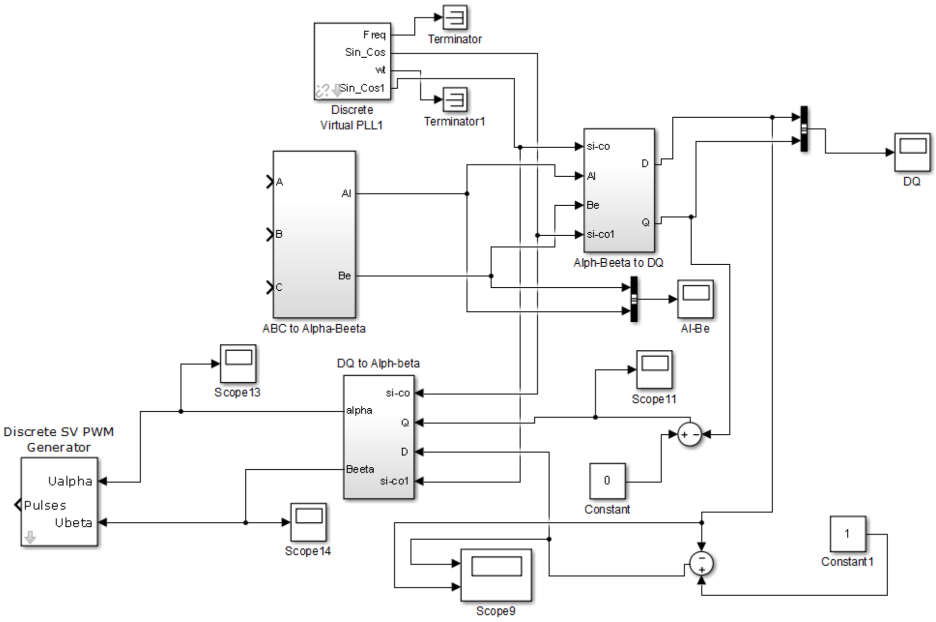

Fig.4 (a): Controlling of D-STATCOM Model

Table 2: D-STATCOM Circuit Parameters

Items	Values
Transmission Line Length	10 km
Inverter Specifications	IGBT based, 3 arms, 6 Pulse, Carrier Frequency =1080 Hz, Sample Time = 5 µs
Capacitor	750×10^{-6} F
Transmission Line Parameters	R = 0.01273 (ohms/km) L = 0.9337 (mH/km) C = 12.74 (nF/km)
Load	R = 0.1 ohms, L = 0.1926 H

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VI. Compensation of Sags with SOFC Based D-STATCOM System for Power Quality Enhancement

To analysis the impact of SOFC with the D-STATCOM test system on the voltage sag compensation, different fault analysis are discussed:

Case 1: Three Phase Fault at 11 kV Distribution Line

The simulation is carried out using MATLAB/Simulink software for analysis three phase fault at the 11Kv distribution line and performance of D-STATCOM is analysed. Voltage sag condition is generated by a three phase fault. A fault is generated at time t = 0.4s, the duration of fault is taken from up to t = 0.6s. The amount of sag is consider 26 percent and voltage drop is considered 0.26 p.u.

To compensate this sag, the voltage is required 0.26 p.u. from D-STATCOM to mitigate the fault. The simulation results are shown with and without sag in fig.5 and the compensation result is shown with high accuracy. The parameter of SOFC is given in Table 3. The approximate fuel cell capacity is 7902 Ampere-Hour (AH).

Table 3: SOFC Parameters-I

Item	Value
Number of Cells in Series	3700
Ideal Standard Potential (V) for Each Cell in Volts	1.18
Absolute Temperature ^{O}K	1273
Initial Current (A)	100
Faradays Constant (C/kmol)	96.487×10^{6}
Universal Gas Constant (J/kmol^{O}K)	8314

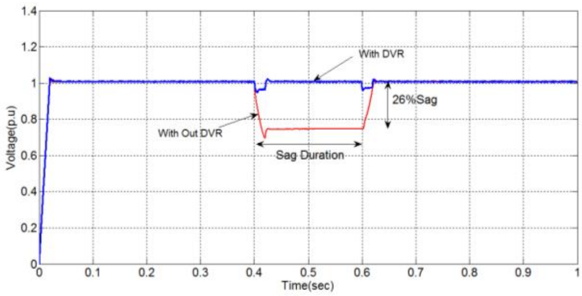

Fig.5: Voltage at the Load Point with and without SOFC Based D-STATCOMfor Three Phase Fault

Case 2: Single Line to Ground (SLG) Fault at 11 kV Distribution Line

The simulation is carried out using MATLAB/Simulink software for analysis Single line ground fault at the 11kV distribution line and performance of D-STATCOM is analysed. Voltage sag condition is generated by a SLG fault. A fault is generated at time t = 0.4 s, the duration of fault is taken from upto t = 0.6s. The amount of sag is consider 17.02 percent and voltage drop is considered 0.1702 p.u. (11 kV=1p.u.)

To compensate this sag, the voltage is required 0.1702 p.u. from D-STATCOM to mitigate the fault. The simulation results are shown with and without sag in Fig.6 and the compensation result is shown with high accuracy. The parameter of SOFC is given in Table.4the approximate fuel cell capacity is 6384 Ampere-Hour (AH).

Table 4: SOFC Parameters-II

System Quantities	Standards
Absolute Temperature ^{O}K	1273
Initial Current (A)	100
Faradays Constant (C/kmol)	96.487×10^{6}
Universal Gas Constant (J/kmol^{O}K)	8314
Ideal Standard Potential (V) for Each Cell in Volts	1.18
Number of Cells in Series	3200

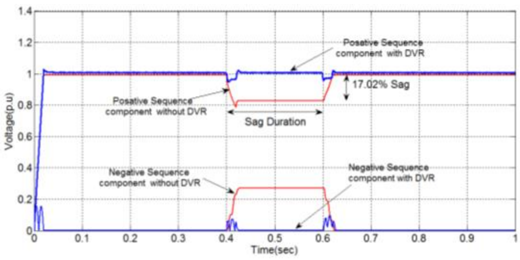

Fig.6: Voltageat the Load Point with and without SOFC Based D-STATCOM for SLG Fault

Case 3: Double Line to Ground (LLG) Fault at 11 kV Distribution Line

The simulation is carried out using MATLAB/Simulink software for analysis LLG fault at the 11Kv distribution line and performance of D-STATCOM is analysed. Voltage sag condition is generated by a three phase fault. A fault is generated at time t = 0.4 s, the duration of fault is taken from up to t = 0.6s. The amount of sag is considered 17.02 percent and voltage drop is considered 0.1702 p.u. (11 kV=1p.u.)

To compensate this sag, the voltage is required 0.1702 p.u. from D-STATCOM to mitigate the fault. The simulation results are shown with and without sag in Fig.7 and the compensation result is shown with high accuracy. The parameter of SOFC is given

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in Table.5 The approximate fuel cell capacity is 6384 Ampere-Hour (AH).

Table 5: SOFC Parameters-III

System Quantities	Standards
Absolute Temperature ^{O}K	1273
Initial Current (A)	100
Faradays Constant (C/kmol)	96.487×10^{6}
Universal Gas Constant (J/kmol^{O}K)	8314
Ideal Standard Potential (V) for Each Cell in Volts	1.18
Number of Cells in Series	3200

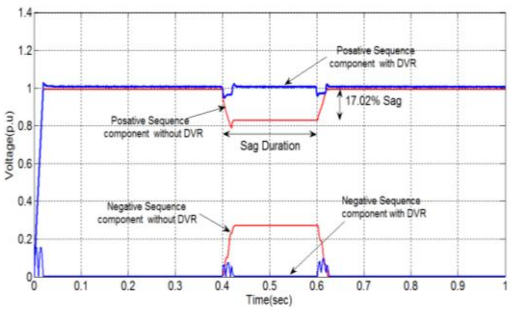

Fig.7: Voltage at the Load Point with and without SOFC Based D-STATCOM for LLG Fault

Case 4: Line to Line (LL) Fault at 11 kV Distribution Line

The simulation is carried out using MATLAB/Simulink software for analysis three phase fault at the 11Kv distribution line and performance of D-STATCOM is analysed. Voltage sag condition is generated by a three phase fault. A fault is generated at time t = 0.4 s, the duration of fault is taken from upto t = 0.6s. The amount of sag is consider 26 percent and voltage drop is considered 0.26 p.u.

To compensate this sag, the voltage is required 0.26 p.u. from D-STATCOM to mitigate the fault. The simulation results are shown with and without sag in Fig.8 and the compensation result is shown with high accuracy. The parameter of SOFC is given in Table 6. The approximate fuel cell capacity is 7902 Ampere-Hour (AH).

Table 6: SOFC Parameters-IV

System Quantities	Standards
Absolute Temperature ^{O}K	1273
Initial Current (A)	100
Faradays Constant (C/kmol)	96.487×10^{6}
Universal Gas Constant (J/kmol^{O}K)	8314
Ideal Standard Potential (V) for Each Cell in Volts	1.18
Number of Cells in Series	3700

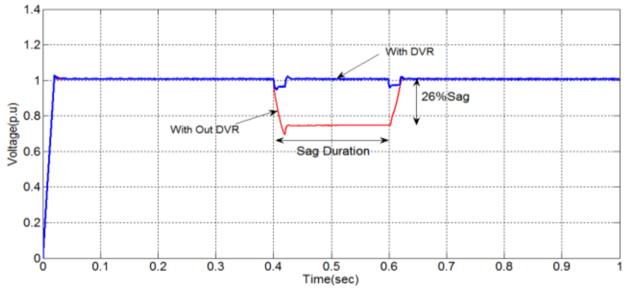

Fig.8: Voltage p.u.at the Load Point with and without SOFC Based D-STATCOM for LL Fault

Conclusion:

A SOFC as a new energy source is suggested forD-STATCOM power circuit and its implementations are discussed for various voltage sag compensation techniques. It is a non-conventional energy source and has capability to mitigate the voltage sag during the symmetrical and unsymmetrical fault condition. It is also observed that this proposed method have capability to mitigate voltage sag with high degree of accuracy and reliability.

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