

Modeling a Fuel Cell Generator set for DC Transient-State studies

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Abstract—In this paper, a Fuel Cell Circuit Model (FCCM) is presented. The model consists of a voltage source in series with a variable resistance controlled by the value of the current produced. Furthermore, in order to find rules and regulations setting operation limits concerning power quality issues in DC networks with Fuel Cells, the results of a survey of appropriate standards is presented. The proposed FCCM is exploited in a series of simulations of representative case studies of D.C. networks, in the well-known computer program PSCAD of Manitoba HVDC Research Center.

Index Terms— circuit models, fuel cells, standards.

I. INTRODUCTION

Fuel Cells (FCs) based on hydrogen is the upcoming favourable if not ultimate renewable energy source conquering all autonomous power systems of inland and waterborne transportation while also introduced in the micro-grid concept of large interconnected networks.

Due to their potential domination, DC nature of networks is coming back and hence, a wide variety of studies have to be carried out from reliability and safety to stability and power quality (PQ). It is worth noting that as outlined in the following, no detailed standards have been released with the possible exception of Germanischer Lloyd's (GL) [4] and IEC [10].

Furthermore, this paper makes an initial effort towards a twofold target: First, to synthesize a circuit model of fuel cell (FCCM hereinafter) capable of performing network studies. Second, exploit this FCCM for studying and analysing certain adverse phenomena along with some elimination measures of theirs via simulations in PSCAD/EMTDC computer environment. Thus, some representative case studies covered

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in the paper include:

- DC current breaking
- Pulsed loads in DC networks
- DC – AC inverters
- Short circuits in DC networks
- Stability in DC networks.

II. THE VOLTAGE – CURRENT CHARACTERISTIC OF A FUEL CELL STACK

The V–I characteristic of a typical FC stack is shown in Fig.1. In general, its potential decreases, as the current demand increases. This descending characteristic curve can be treated as comprising three main parts, with each one depending on different loss type as described in the following [15]:

A. Activation Polarization: Activation polarization is present when the rate of an electrochemical reaction at an electrode surface is controlled by sluggish electrode kinetics. In other words, activation polarization is directly related to the rates of electrochemical reactions. There is a close similarity between electrochemical and chemical reactions in that both involve an activation barrier that must be overcome by the reacting species.

B. Ohmic Polarization: Ohmic losses occur due to resistance to the flow of ions in the electrolyte and resistance to the flow of electrons through the electrode materials. The dominant ohmic losses, through the electrolyte, are reduced by decreasing the electrode separation and enhancing the ionic conductivity of the electrolyte.

C. Concentration Polarization: As a reactant is consumed at the electrode by electrochemical reaction, there is a loss of potential due to the inability of the surrounding material to maintain the initial concentration of the bulk fluid. In this way, a concentration gradient is formed. Several processes may contribute to concentration polarization: slow diffusion in the gas phase in the electrode pores, solution/dissolution of reactants/products into/out of the electrolyte, or diffusion of reactants/products through the electrolyte to/from the electrochemical reaction site.

Each type of loss affects the voltage drop in a range of current values. Thus, type 'A' dominates on low current values, type 'B' on medium, while type 'C' is related to high current values, i.e. close to the operating limits of the fuel cell.

III. FUEL CELL CIRCUIT MODEL (FCCM)

When current is drawn from a typical voltage source, the

potential decreases according to the equation:

$$V = E - i \cdot r \tag{1}$$

where:

V: the terminal voltage

E: the internal voltage (no load terminal voltage)

i: the current

r: the internal resistance of the source

The circuit representation of equation (1) is shown in Fig. 1. Internal resistance r models the internal losses of the source causing voltage drop and it is equal to the gradient of V – I characteristic.

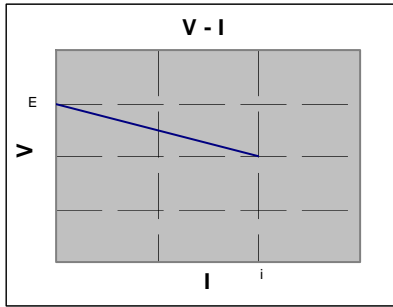


Figure 1: Voltage drop at a typical voltage source.

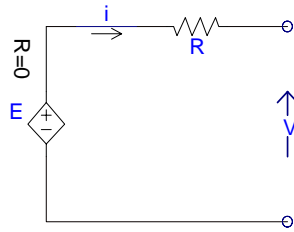


Figure 2: Representation of a typical voltage source by PSCAD.

Similarly in the case of FCs, each type of loss can be modeled as a resistance causing voltage drop, while representing the gradient of the graph at the corresponding current regions. Unlike to the typical voltage source, the losses of a FC, vary as a non – linear function of the current. The largest gradient value is that of the first region (A), while the smallest is that of the second region. The resistance of part C has an intermediate value close to the first one. That is:

$$r_A > r_C > r_B \tag{2}$$

The model used to describe the FC source, consists of a voltage source of constant value connected in series with a variable resistance representing both the non – constant gradient of the V – I characteristic and the losses of the FC.

The variable resistance values dependent on the flowing current can be controlled via a two – column look – up table, the first column of which is the current, whereas the second is the resistance value, see Fig. 4b. The circuit model yielded as synthesized in PSCAD is shown in Fig. 3, while the numerical data are presented in the Appendix.

IV. FUEL CELL CIRCUIT MODEL (FCCM)

As this work has been focused on investigating power quality issues on DC networks where FCs are installed, a significant number of regulations of classification societies

and organizations [1]-[14] have been sought, as listed in Table I.

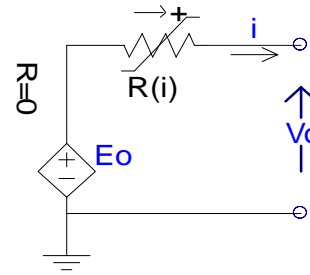
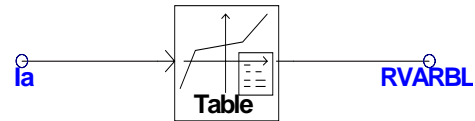


Figure 3: Electrical equivalent of a FC



(a)

I (A)	r (Ohm)
0	2.5
12	0.2
110	1

(b)

Figure 4: The r-I dependence via a look – up table

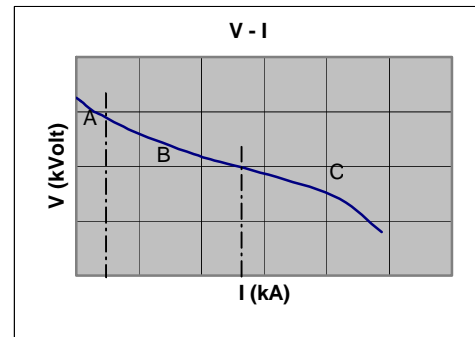


Figure 5: The V – I characteristic by the FCCM

Table I: Organizations and Classes

ORGANIZATION	CLASS
IEC	Lloyd's
EN	Bureau Veritas
IEEE	Germanischer Lloyds
NFPA	KRS
STANAG	HRS
ISO	DNV
	RINA

Anyhow, there have been no rules or regulations for power quality on DC networks with FCs. The only references on FC, in general are these of Germanischer Lloyds (GL) [4] and IEC [10], but interest is focused merely on proper hydrogen

handling. Thus, GL [4] do not have specific rules on power quality of FCs. There is a new chapter about them, in which information is provided mainly about FC construction. As far as power quality is concerned, reference is made to already existing rules on electric machines.

IEC [10], in 2006, published a series of rules about FCs (62282), but does not set specific limits on power quality.

Therefore, in order to have a set of rules as a working tool, the following set has been considered taking into account the aforementioned standards (see Table I), applied to DC ship circuits (including DC machines, batteries and capacitors):

- Permissible voltage fluctuation in steady state: $\pm 3\%$
- Permissible voltage fluctuation in transient state: $\pm 10\%$
- For short – circuit studies, the most applicable standards are those of IEC 61660 – 1 for battery circuits.

V. SIMULATIONS

A. DC current breaking

Current breaking in DC circuits is a difficult task as the current has no natural zero, where the breaker can trip to perform circuit distortion. Therefore the current zero has to be created in an artificial manner by injecting a current of inverse polarity via an auxiliary sub-circuit.

The circuit used is presented in Fig. 6 and consists of [16]:

- The main breaker branch which is initially closed. The proper time it opens and the phenomenon begins.
- The second branch is the auxiliary circuit injecting inverse current and consists of a power electronic switch e.g. a GTO, a charged capacitor, a resistance and a voltage source.
- The third branch is a varistor used to suppress any developed overvoltage exceeding insulation level.

The proper time, the second branch creates negative current and the breaker opens. The behaviour of the circuit is as presented in Fig. 7 – 9 via the $V - t$, $I - t$ and $V - I$ waveforms. At the beginning, it comes to a stable condition, with specific voltage and current. The time the breaker opens, a significant overvoltage is developed across the circuit breaker terminals, the value of which is limited by the varistor.

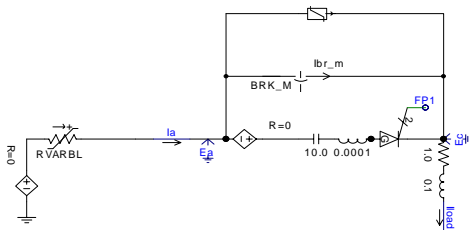


Figure 6: The DC current breaking circuit

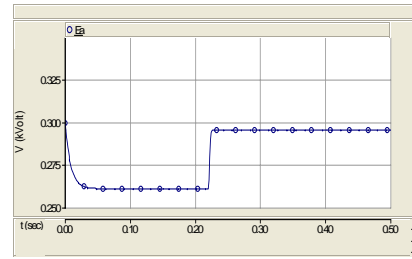


Figure 7: Voltage – time graph

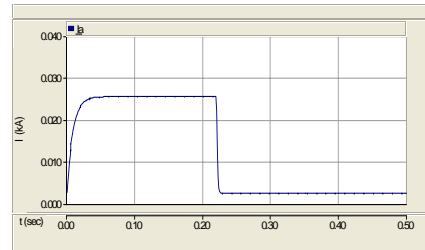


Figure 8: Current – time graph

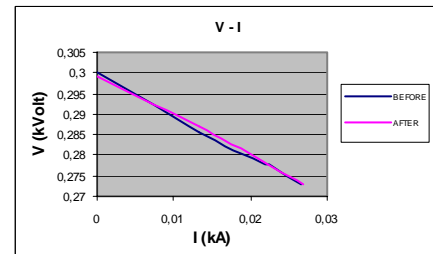


Figure 9: Voltage – current graph

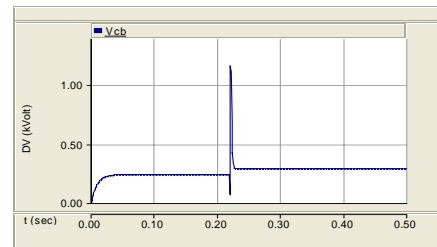


Figure 10: Voltage difference – time graph

B. Pulse Loads

Pulse loads [16] last for very little time (a few milliseconds) and have huge demand in current. They are very popular in modern applications, especially in military warships. The behaviour of a circuit with a FC is looked into, considering the difficulty of FC to respond quickly to power fluctuations.

Fig. 11 shows the model used to study the response of a circuit with pulse load. It consists of the FCCM, connected in series with the load. The resistance with the larger value represents the constant load of the corresponding to low power demand circuit. On the other hand, the pulse load is parted from a GTO in series with a small valued resistance. When the GTO lets current to go through the branch and in combination with the small resistance, the pulse load is emulated. Between the load and the FCCM there is a sketchy distribution cable, which further contributes to voltage drop.

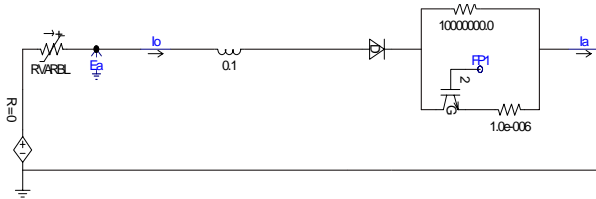


Figure 11: Pulse load circuit

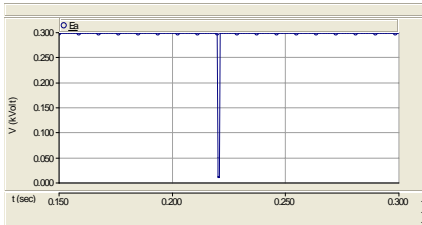


Figure 12: Voltage – time graph

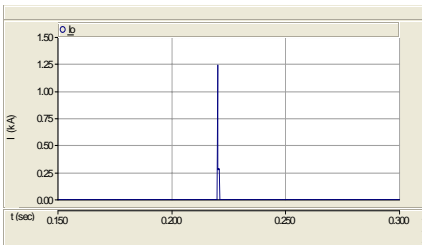


Figure 13: Current – time graph

The circuit creates indeed a pulse load with the expected characteristics. It demands big value of current for a few μ s. This causes the voltage to nearly nullify. However this voltage drop is abide by the rules, which set that a voltage source must be so designed as to tolerate this kind of loads. Thus, IEC 60092 – 101 allows transient voltage deviation of up to 2500V for voltage source of 220V DC for a duration of 1.2 up to 50 μ s – i.e. more than 1100%-, which is mainly originated from lightning strikes, however it can match this case, too.

3. DC – AC inverters

In this case a 6 – pulse inverter bridge comprising GTOs is considered. For this purpose, three pairs of GTOs are used. GTOs let the current pass through in a fully controllable manner and create positive or negative current. Fig. 14 represents the circuit on PSCAD used for this simulation. The inverter load considered consists of passive RL elements.

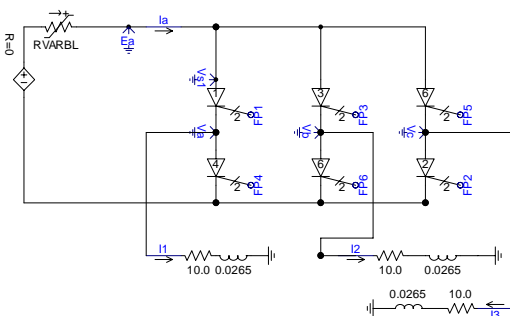


Figure 14: Circuit of inverter by PSCAD

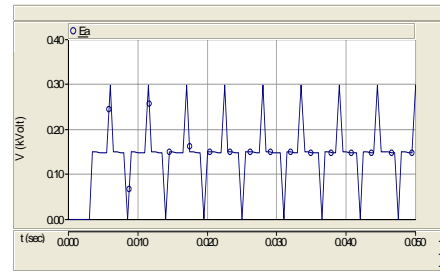


Figure 15: Graph of FC voltage vs time

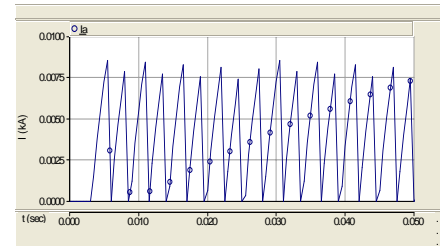


Figure 16: Graph of FC current vs time

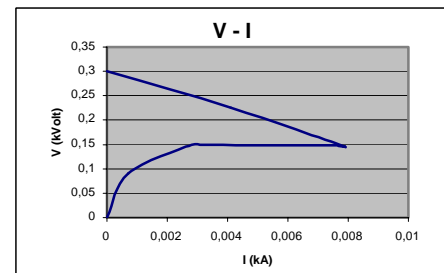


Figure 17: Graph of FC voltage vs FC current.

As shown in Fig. 15 and 16, both current and voltage comprise besides the mean DC value, an apparent AC component. This undesired AC component on the DC side is due to the switching operation mode of the inverter and has to be provided by the FC, changing the V-I characteristic into the one shown in Fig. 17, unless a filter is installed eliminating this contribution of the FC.

4. Short – circuit

The short – circuit of the fuel cell takes place when it is connected to a circuit of almost zero resistance. Therefore, the current running the circuit has a large value. The dynamic model of the short – circuit can be a circuit breaker connected to earth and as soon as it closes a large value current flows in the circuit. The circuit used to represent the short – circuit is that of Fig. 18. The requested time (0.2sec) the breaker closes and the FC faces the short – circuit.

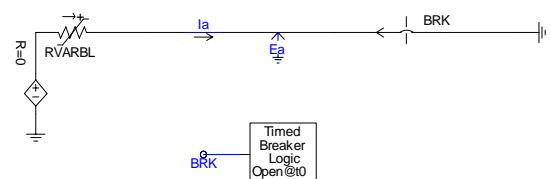


Figure 18: Circuit used to represent the short – circuit

For this case, IEC 61660 – 1 for batteries is used on the grounds that, unlike motors, neither fuel cells nor batteries do have any rotating parts. According to the IEC 61660 – 1 the peak value of the current during short – circuit at the battery terminals, is given by the equation:

$$I_{pB} = \frac{E_B}{R_{BBr}} \quad (3)$$

where:

I_{pB} : Peak value of short circuit current

E_B : No-load voltage of the battery

R_{BBr} : Total resistance of the battery

Similarly, the peak value of the short circuit current, in the case of fuel cell, is calculated as:

$$I_{pFC} = \frac{E_{FC}}{R_{FC}} \quad (4)$$

The question is which one of the three resistance values should be used to calculate the value of the short – circuit current. According to (4) the highest value of the current is calculated if the smallest value of resistance is used. So the FC must be so designed as to tolerate the largest possible value of short – circuit current. In that case if the smallest resistance is used, the peak value is, (see Appendix for numerical data):

$$I_{pFC} = \frac{300}{0.2} A = 1500 A \quad (5)$$

The simulation where the non – linear behaviour of the FC internal resistance has inherently been taken into account, provides a peak value of 1.46kA, as shown in Fig. 19, i.e. very close to –slightly lower than- the result of (5). Thus, it can be concluded that calculating short circuit currents with the smallest resistance leads to results on the safe side (slightly worst than the precise ones).

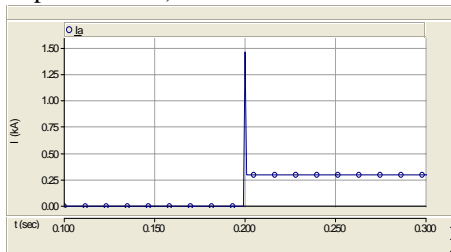


Figure 19: Peak value of short circuit current in PSCAD simulation

5. Voltage stability in DC networks.

The stability of a DC network is affected either by the circuit capacitor used to keep the output voltage constant or the internal resistance of the voltage source [18]. In the following, it is examined what happens if the resistance is of variable value, as in the case of FCs.

An electric resistance behaves as damping factor. If the value of the resistance (r) is larger than the one of the load (R) the oscillation almost does not exist. If it is smaller, the circuit takes some time to come to stability and the deviation of the voltage is quite apparent.

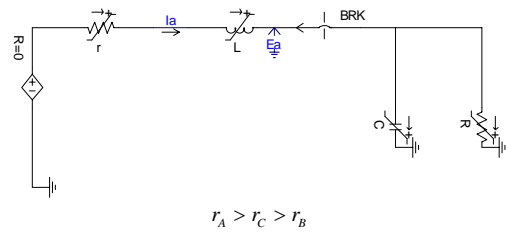


Figure 20: Circuit model for Voltage stability study

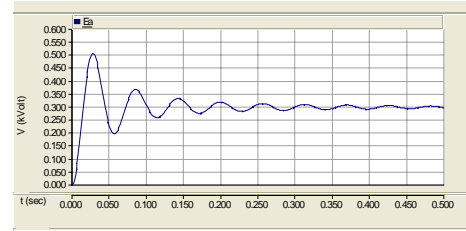


Figure 21: Effect of a variable resistance to the circuit stability

In the case of Fig. 21, variable resistance is used. The oscillation is affected by all the three partial resistances of r , see (2). The phenomenon lasts as much as if there was not variable resistance and only the smallest resistance (r_B) affects the circuit. The frequency of the oscillation is determined by the effect of the biggest resistance, i.e. (r_A). The first peak of value is almost equal to that of the medium valued resistance (r_C). The width of the oscillation comes out of the combination of all the resistances.

The closer the variable resistance to the one of the load, the faster the circuit comes to stability. Fig. 22 shows how the oscillation is affected when the partial resistances composing the variable one are close, in value, to the one of the load. Fig. 23 shows the same effect when the internal resistance is larger than the one of the load; in both cases the oscillation vanishes. The value of current obviously depends on all three resistances.

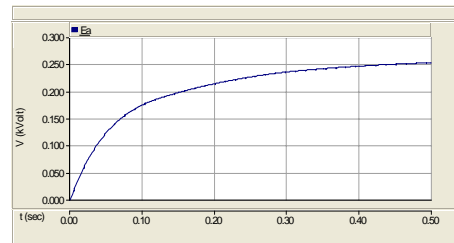


Figure 22: Mean value of variable resistance close to that of the load

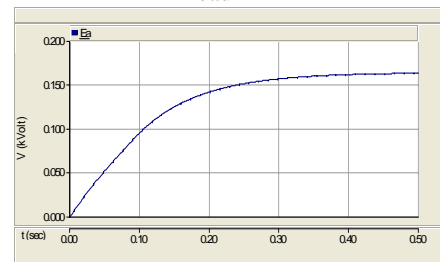


Figure 23: Mean value of variable resistance larger than this of the load

Finally, an interesting case is when only the first resistance is of higher value than the one of the load. In general in a $V - I$ characteristic of a fuel cell r_A is the biggest of the three, see (2). However, comparable to this value is the third one, i.e. r_C . Thus, the case in which only r_C is of higher value than both r_A and load resistance R , is also examined.

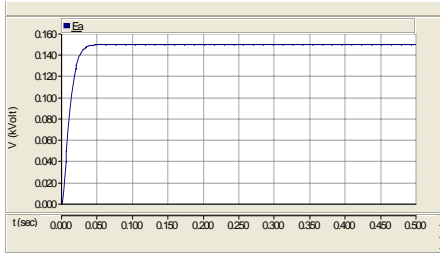


Figure 24: First resistance bigger than the one of the load

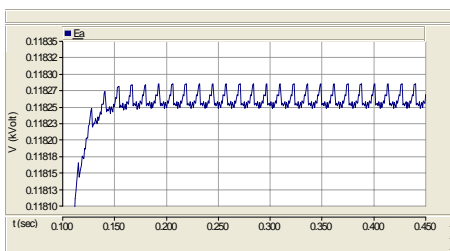


Figure 25: Third resistance bigger than the one of the load

As shown in Fig. 24 and 25 when one of the resistances is of much higher value than the load, the circuit comes to stability fast. In Fig. 24 the first resistance is of higher value than that of the load. The calculated voltage is located in the third part. In this case there is no oscillation because the resistance of the third part is of similar value to r_A . On the other hand, in Fig. 25, though r_C exceeds the value of the load, a non-significant oscillation is created. The mean voltage results in a value in the second part of the graph, in which r_B is dominant and affects the stability alone. Since the resistance of this part is of quite lower value than R , it causes this oscillatory phenomenon.

VI. CONCLUSIONS

In this paper, a Fuel Cell Circuit Model (FCCM) is presented. The model consists of a voltage source in series with a variable resistance which is controlled by the value of the current.

Furthermore, organizations and classes have been looked into in order to find rules and regulations set operation limits of power quality in network with FC's, but with no results. Hence, the following set of standards have been considered as a recommended working implement of rules:

- Permissible voltage fluctuation in steady state: $\pm 3\%$,
- Permissible voltage fluctuation in transient state: $\pm 10\%$,
- Permissible voltage fluctuation for extremely fast transients (of duration $< 50\mu s$): $\pm 1100\%$,

- Short – circuits studies according to IEC 61660 – 1 for battery circuits.

Moreover, the proposed FCCM has been exploited in a series of simulations of representative case studies of D.C. networks, in PSCAD, the computer program of Manitoba HVDC Center.

APPENDIX

The fuel cell used for the examples has the following characteristics:

$$E_{FC} = 300\text{Volt}$$

$$r_1 = 2.5\text{Ohm}$$

$$r_2 = 0.2\text{Ohm}$$

$$r_3 = 1\text{Ohm}$$

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