INTERNATIONAL JOURNAL OF CIRCUITS, SYSTEMS AND SIGNAL PROCESSING
DOI: 10.46300/9106.2022.16.126

Volume 16, 2022

Design consideration of charging station with hybrid energy sources

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Received: October 17, 2021. Revised: April 13, 2022. Accepted: May 6, 2022. Published: June 23, 2022.

Abstract— In current research a hybrid autonomous supplying system for electric vehicles applications is presented. The hybrid system is consisted of fuel cell, micro gas turbine and supercapacitor. There are realized with averaged models in MATLAB/Simulink environment. The supplying elements are connected to a DC bus for charging a different type of EVs. In this case as a load is use two EVs: BMW-i3 and Nissan Leaf. This system can operate autonomously in hard-to-reach places where there is no supplying from the distributed grid and other sources. These places could be remote holiday villages, research centers positioned at hard-to-reach places and also for production of agricultural crops with the aids of electric vehicles. This requires the necessity for searching of different structural and conceptual solutions for production and storage of electric energy. An optimization problem is resolved in order to reduce the value of the capacitance of the supercapacitor with which it will decrease his price. Thus, it also decreases the price for construction of the entire charging station. Recently, the usage of natural gas and his transportation is well organized which can contribute for assuring of the reserved energy for the autonomous charging station.

Keywords— electric vehicles, charging station, fuel cell, micro gas turbine, supercapacitor, design consideration.

I. Introduction

RECENTLY, the necessity of development of hybrid autonomous system for supplying a different load such as small houses, electric vehicles (EVs) and etc. significantly increase. Basically, this is caused by the enormous changes in the industry which leads to challenges in front of the users, system operators and different companies. The decentralization is one of the main drivers which causes these transformations [1]. The usage of the renewable energy sources in transportation sector significantly can decrease the usage of the conventional power supply. Thus, the harmful emission and the local pollution can be decreased which would improve the quality of life.

Likewise, it is considered that the usage of a solar and wind energy from photovoltaic (PV) and wind generator (WG) might be useful for multiple application [2],[3]. Although, this renewable energy sources are strongly dependent from the weather conditions such as wind speed, solar radiation and etc. In this case the PV and WG may not be provide the necessary load demand. Also, the cost of the centralized grid distribution significantly increases. Another problem related to grid distribution is that there is hard to reach places which don't allows electrification.

The basic idea is to use decentralized power supply with the help of different renewable power sources for diminutions of the harmful emission and preservation of the Planet. A possible solution which is appropriate for usage in autonomous power supply could be a supercapacitor, fuel cell. The development of technologies and the research of the different methods of control of the supercapacitors and fuel cells can significantly improve the operation of the autonomous hybrid supplying system [4].

Lately, the micro gas turbine can be used for hybrid production of electric energy. The usage of the micro gas turbine as a supplying energy source could be useful for decreasing of the loading of the elements in the hybrid system and could be assure an additional energy source for balancing of the energy flows in the system. The micro gas turbine has the following advantages:

- low specific investments;
- higher efficiency – around 80%;
- in short terms for construction;
- high degree of automation and reduction of service personnel;
- great maneuverability of the modules and fast commissioning;
- power can be easily adjusted in a wide range;
- environmentally friendly - reduces carbon and nitrogen oxide emissions and no emissions of sulfur oxides and dust.

The fuel cell converts chemical energy of the fuel into electrical energy without the usage of the combustion. As a combustible is used hydrogen, natural gas, methane and etc. Due to this reason the fuel cells are environmentally friendly and it can be used for production of the "green" energy. In the hybrid system they are combined with different devices for production and energy storage such as battery, supercapacitors and etc. [5],[6]. The efficiency of the fuel cells varies between 30-40 %.

Due to the economic and environmental advantages of the separate modules of the proposed autonomous hybrid system this research would help for development of the technologies and the usage of pure energy.

II. Modeling of Hybrid System

In this research a hybrid autonomous system with micro gas turbine, fuel cell and supercapacitor are studied. The block diagram of the system is presented in Figure 1. In this case a for load profile are used two electric vehicles.

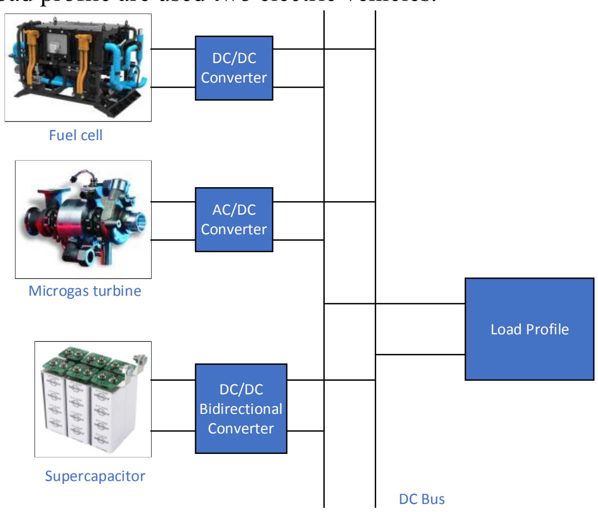


Figure 1. Block diagram of the hybrid system

A. *Modeling of gaz turbine*

In the current study realized and simulated gas turbine is a single shaft 30kW micro turbine generation system based on Capstone C30 turbine. It exists two basic solutions for design of micro gas turbine. The first one is to use a single shaft with compressor, permanent magnet synchronous machine (PMSM) and turbine. The frequency of the machine in generator mode can vary between 1500 and 4000 Hz. The second one is used a technology with split design. In this case the turbine rotates at 3600 rpm and it is used a gearbox for connection to the conventional generator. In this research is used a micro gas turbine with single shaft due to their advantages such as stability, higher efficiency and compact structure.

The micro gas turbine is consisted of turbine, PMSM, compressor, combustion chamber, power electronic converters and heat recuperator. The heat recuperator is defined by the size of the heat load for which is designed the module. The electrical power of the gas turbine depends of the thermal power. This a distributed system which is supplied by a gas. In Figure 2 the block diagram of the control of the MT is presented. It can be observed that the gas turbine operates on the basic principle of the thermodynamic which is known as a Brayton's cycle [9].

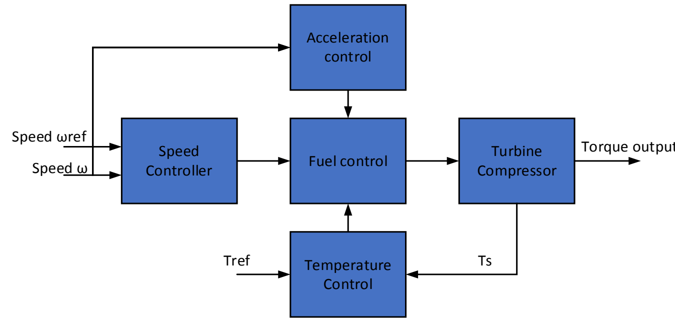


Figure 2. Block diagram of control system of the micro gas turbine.

Simulink implementation of the Rowen model [10] of the gas turbine is shown in Figure 3.

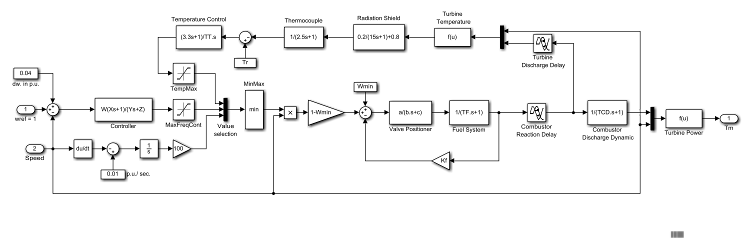


Figure 3. Simulink model of micro gas turbine

B. *Modeling of permanent magnet synchronous machine (PMSM).*

The values of the preset model of the PMSM are: torque – 87.75 Nm, DC voltage – 560, rounds per minute (RPM) – 3000 and can be described with the following equations [10]:

$$\frac{di_d}{dt} = \frac{1}{L_{ds}+L_{is}}\left(-R_s i_d + \omega_e\left(L_{qs}+L_{is}\right)i_q + u_d\right) \quad (1)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs}+L_{is}}\left(-R_s i_q - \omega_e\left[\left(L_{ds}+L_{is}\right)i_d + \psi_f\right] + u_q\right) \quad (2)$$

Where d and q are physical quantities which are transformed in d-q rotating reference frame, Rs is the stator resistance, L_d and L_q are inductances of the d and q axis, L_{ds} and L_{qs} are the stator inductance of the d and q axis, Lis is the inductance between the phases, L_{id} and L_{iq} are the leakage inductances, ψ_f is permanent magnetic flux, ω_e is electrical rotating speed which can be defined by the following equation:

$$\omega_e = p\omega_g \quad (3)$$

Where p is the number of pole pairs of the generator.

The electromagnetic torque can be described by the following equation [10]:

$$\tau_e = 1.5p\left(\left(L_{ds}-L_{is}\right)i_d i_q + i_q\psi_f\right) \quad (4)$$

C. *Modeling of fuel cell*

The simplified model is a stack of fuel cells supplied by controlled source of voltage connected in series with internal resistance. The realized model is presented in Figure 3. The controlled source of voltage is described with the following equations (5)-(8) [11]:

$$u_{fc} = \left(E_{oc} - N.A.\ln\left(\frac{i_{fc}}{i_0}\right)\right).\left(\frac{1}{s.Td/3+1}\right) \quad (5)$$

$$N\cdot A = \frac{(V_1 - V_{nom})\cdot(\mathrm{I}_{max}-1) - (V_1 - V_{\min})\cdot(I_{nom})}{\ln(I_{nom})\cdot(I_{\max}-1) - \ln(I_{\max})\cdot(I_{nom}-1)} \quad (6)$$

$$R_{ohm} = \frac{V_1 - V_{nom} - N\cdot A\cdot \ln(I_{nom})}{I_{nom}-1} \quad (7)$$

$$i_0 = \exp\left(\frac{V_1 - E_{OC} + R_{ohm}}{N\cdot A}\right) \quad (8)$$

Where E_{OC} is the voltage of the open circuit, N is the number of cells, A is the slope of Teifel, i_0 is the current, T_d is the time response of the system, i_{fc} is the current of the fuel cell, u_{fc} is the voltage of the fuel cell.

The equations (6) is described in [12] and it is the voltage of the stack and in this case are take into account only the active power losses. In [12] these losses are modeled electrical with parallel RC circuit. Consequently, when we have a rapid change of the current flow in the stack, the voltage of the FC will decrease 3 times of times constant. This process is described with equation (5) with transfer function of first order $\frac{1}{sT_d/3+1}$ where T_d is the time constant for establishment of voltage of the stack of FC. The equation (3-12) describes the full voltage of the fuel cell stack and the internal losses of the cells caused by electrodes and electrolyte resistance are given.

The presented simplified model of the fuel cell allows simulation at the following nominal condition: pressure and temperature. The reverse diode prevents from the reverse current flow.

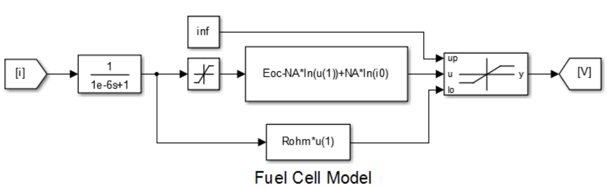


Fig 4. Simplified model of fuel cell

D. *Modeling of supercapacitor*

Thoroughly the Supercapacitor (SC) model is realized on the basis of formulas given in [14]-[16]. The Supercapacitor block implements a model parameterized to represent most popular types of supercapacitors. The block implements the Stern Volmer equation. Not modeled the self-discharge phenomena. The rest assumptions are: Internal resistance and capacitance are assumed constant during the charge and the discharge cycles. The model does not take into account temperature effect. No aging effect is taken into account. Charge redistribution is the same for all values of voltage. The block does not model cell balancing. Current through the supercapacitor is assumed to be continuous.

The Simulink model of the SC is presented in Figure 5.

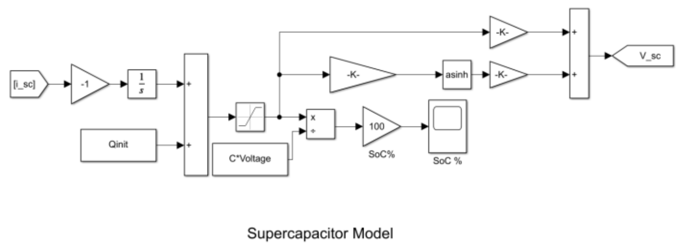


Fig 5. Simplified model of supercapacitor in MATLAB/Simulink

The mathematical model of the SC can be described with the following Stern equations [17]-[20]:

$$V_{sc} = V_T - R_{dc} i_{dc} \quad (9)$$

$$V_T = \frac{N_s\, r}{N_p\, N_e\, \varepsilon\, \varepsilon_0\, A} Q + \frac{N_s\, N_e\, 2\,RT}{F}.a\sinh\left(\frac{Q}{N_p\, N_e^2\, A\sqrt{8\,RT\,\varepsilon\,\varepsilon_0\, c}}\right) \quad (10)$$
$$= \alpha.Q + \beta.a\sinh(\gamma.Q)$$

Where

$$\alpha = \frac{N_s\ r}{N_p\ N_e\ \varepsilon\ \varepsilon_0\ A} \quad (11)$$

$$\beta = \frac{N_s\, N_e\ 2\,RT}{F} \quad (12)$$

$$\gamma = \frac{1}{N_p\ N_e^2\ A\sqrt{8\ RT\ \varepsilon\ \varepsilon_0\ c}} \quad (13)$$

$$Q = \int i_{SC} dt + Q_{init} \quad (14)$$

In these equations (11) to (13) the constants *α, β* and *γ* are the rates of change of the supercapacitor during the different time intervals. They basically depend of number of supercapacitors connected in series and in parallel [21]-[23].

The following notations are used:
V_{sc} is the output voltage of the supercapacitor;
Np is the number of parallel capacitor;
Q is the electric charge;
Q_{init} is the initial electric charge;

A - Interfacial area between electrodes and electrolyte (m^2). If the influence of temperature T is neglected, then *A* will be proportional to $C\ N_s\ /\ N_p$, i.e., $A \sim \frac{C\ N_s}{N_p}$

c- molar concentration (mol m−3), where $c = \frac{0.86}{8\,N_a\ r^3}$
and *Na*=6.02214.1023 is Avogadro constant (mol^{-1})
Temp - operating temperature of the supercapacitor (C°),
Temp = 25, i.e. $T = T_{emp} + 273.15$
Ne - number of layers of electrodes related to the Stern model. Only a single-layer model is considered, i.e. *Ne* = 1

DOI: 10.46300/9106.2022.16.126

F - Faraday constant, F=96485.3383, s A / mol
r - molecular radius related to the Stern model (m), r = 1.23e-9*R* - ideal gas constant (kg m2 s−2 K−1 mol−1), R=8,3145
ε0 - permittivity of free space (F m−1)
ε - relative permittivity of material,
$\varepsilon\varepsilon_0 = 6{,}0208 . 10^{-10}$.

The *SOC* is calculated as $SOC = \frac{Q_{init} - \int_0^t i(t)dt}{Q}$.

TABLE 1. PARAMETERS FOR THE FUEL CELL

Parameters	Designation	Value
Voltage of the 0 Amperes	E_{oc}	400[V]
Voltage of the 1 Amperes	V_1	380[V]
Nominal current	I_{nom}	285[A]
Nominal voltage	V_{nom}	300[V]
Maximal current	I_{max}	347.3[A]
Minimal voltage	V_{min}	288[V]

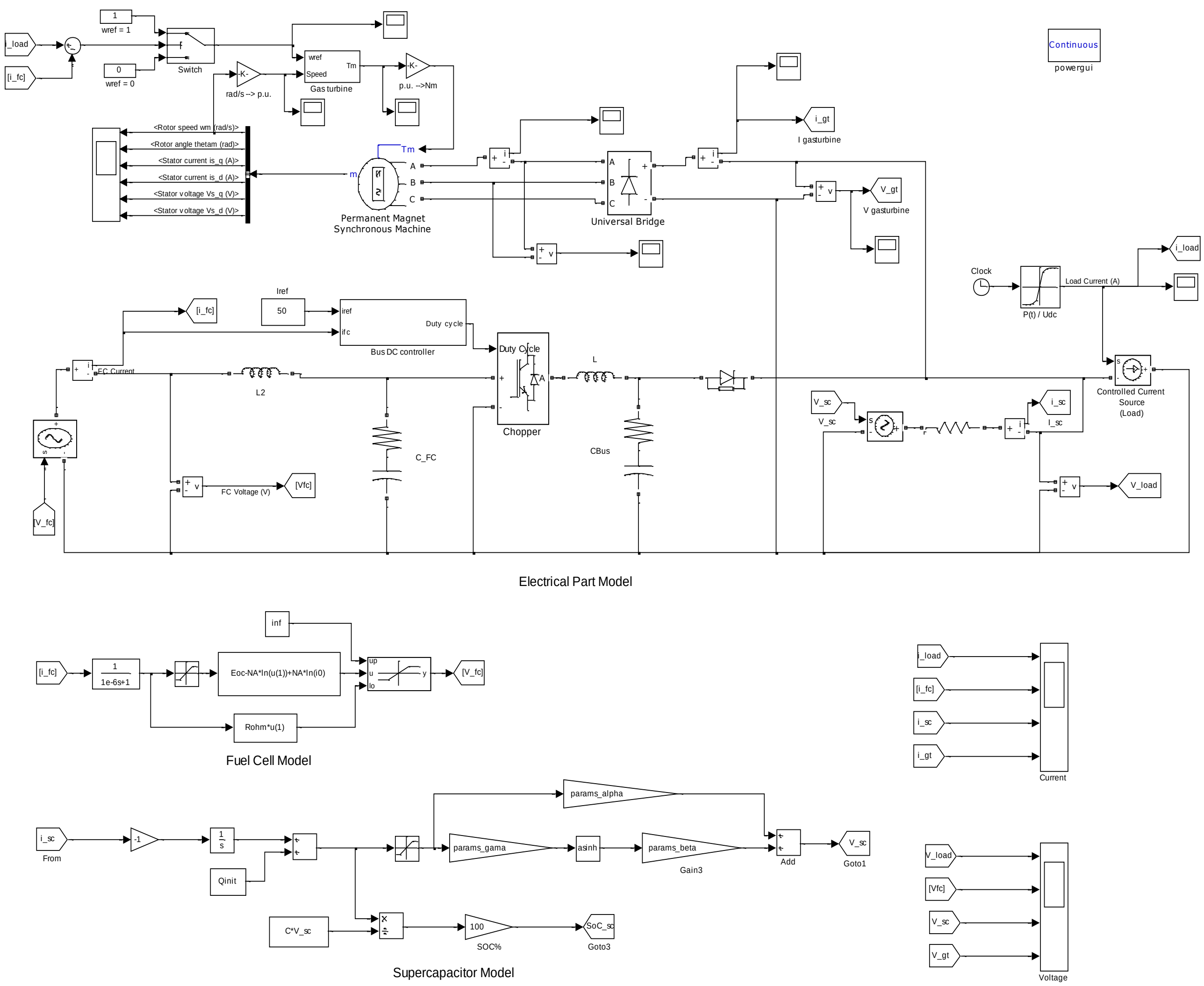


Figure 6. Mathematical model of the whole system in MATLAB/Simulink

In our research we assume thatthe influence of temperature *T* is neglected, then Q_{init} can be calculated as follows

$$Q_{init} = \frac{C\, V_{init}\, \varepsilon\varepsilon_0}{r}\left(A\, e^{-\frac{N_s}{B\, N_p}} + D\right) = 2.312e{+}4,$$

where A, B and D are constants.

TABLE 2. PARAMETERS FOR THE SUPERCAPACITOR

Parameters	Designation	Value
Capacitance	C	100[F]
Internal resistance	R_{dc}	8.9[mΩ]
Initial voltage	V_{init}	288[V]
Number of series capacitors	N_s	6
Number of parallel capacitors	N_p	1

E. The whole system model

TABLE 3. PARAMETERS FOR THE MICRO GAS TURBINE

Parameters
Fuel Demand Signal: Max Limit (MAX=1.5, pu), Min Limit (MIN= - 0.1, pu)
Valve Positioner: Parameter (a=1), Time Constant (b=0.05, s), Parameter (c=1)
No Load Fuel Consumption (Wmin=0.23)
Fuel System Time Constant (TF=04, s)
Fuel System External Feedback Loop Gain (KF=0)
Delay of Combustion System (ECR=0.01, s)
Transport Delay of Turbine and Exhaust System (ETD=0.02, s)
Compressor Discharge Lag Time Contant (TCD=0.2, s)
Rated Exhaust Temperature (TR=950, degF)
Temperature Controller Integration Constant (TT=527, degF)

In addition, the most efficient mode of operation of the gas turbine is when the appropriate amount of fuel is supplied through the switch control, ensuring the rotation of the shaft within the limits of the capacitor $\pm 15, \%$ from the nominal rounds [24]-[28]. This can be achieved with switching of the reference value of the shaft rotation between its nominal value and zero, i.e. $w_{ref} = 1, p.u.$ or $w_{ref} = 0, p.u.$

Where ω_{ref} is the reference value of the shaft rotation in relative unites. This defines the optimal operation modes with the proper value of the capacitor.

III. OPTIMIZATION PROCEDURE

The most efficient operating mode of the FC is when the current is a constant, $i_{FC\ ref} = const.$. This is due to the fact that the proposed system operates in isolation from the distributed grid and at one point there is no place to store excess energy [29]-[31]. To solve this problem, an

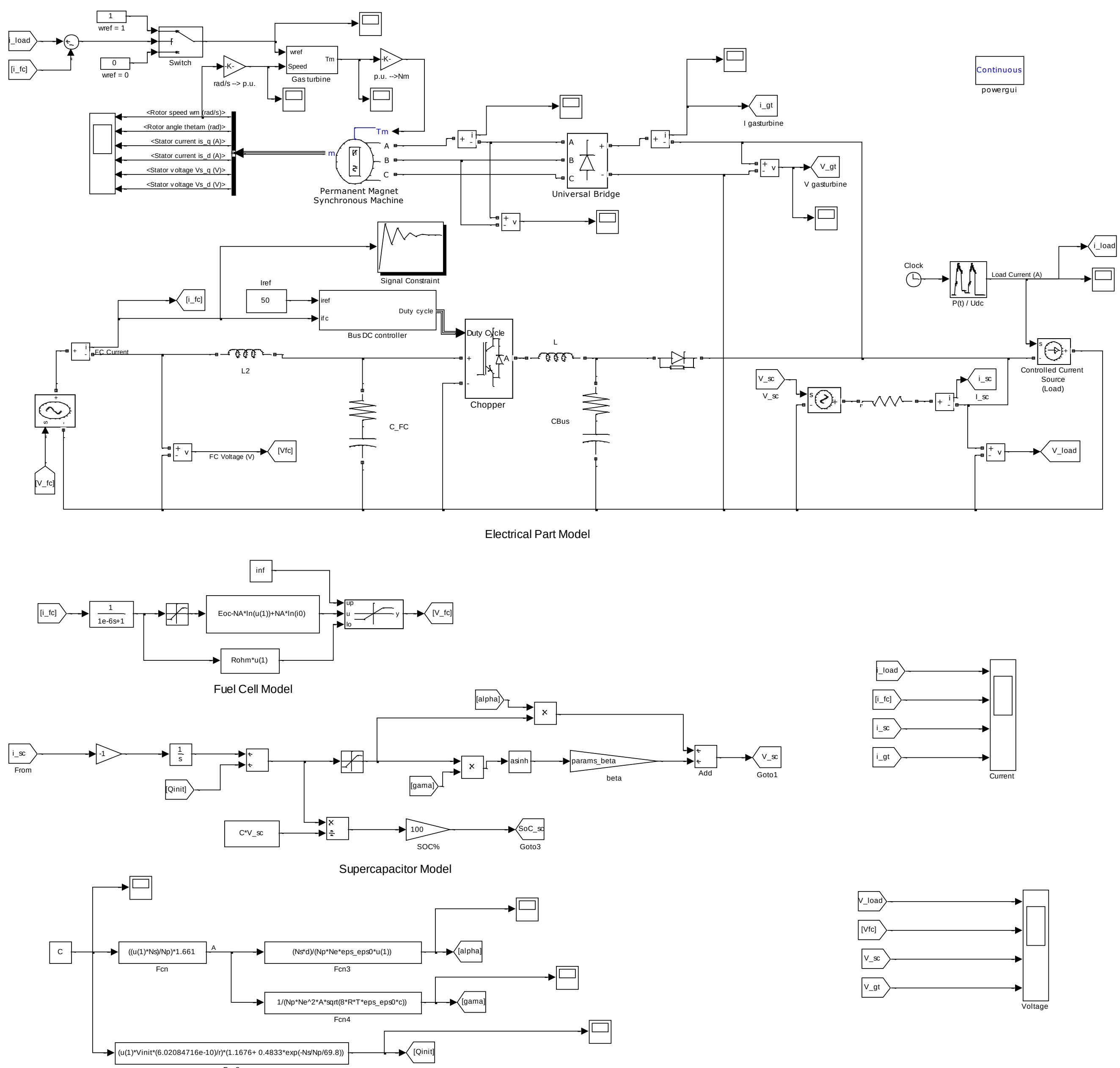


Figure 7. Mathematical model of the whole system in MATLAB/Simulink with optimization procedure

DOI: 10.46300/9106.2022.16.126

optimization procedure for selecting the optimal value of capacitor C is proposed below.

To optimize the value of capacitor C, the optimization procedure built into the “Signal constraint” block is added (Figure 7). Blocks are also added to the calculated parameters α , γ and Q_{init} of the SC model (Figure 7).

The reference trajectory is entered $i_{FC\ ref} = 50, A$ and capacitor limits are set $C_{\min} \le C \le C_{\max}$

IV. Results

In Figures 8 to 13 the GT switch (at value of this variable 1 the turbine works, and at 0 - it is switched off), the current of the load (load profile), the current of the fuel cell, the current of the supercapacitor and the current of the GT are presented. For the first three figures is used one load after that the load is changed. For realization of this simulation results are used several different values of the fuel cell and the supercapacitor. It can be observed that when the current of the fuel cell has minimal value of 50 A, the supercapacitor maintain the necessary current for this typical load. In the Figure 10 it can be observed that the GT is off. In this case the other power supply assures the necessary power demand.

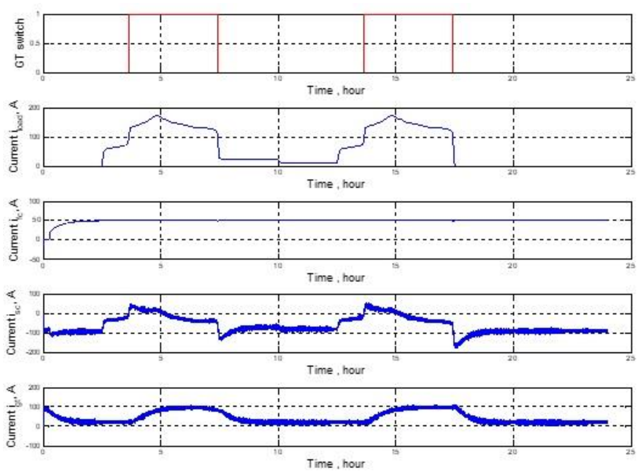


Figure 8. Results of the first load profile with fuel cell 50A and capacitor 100F

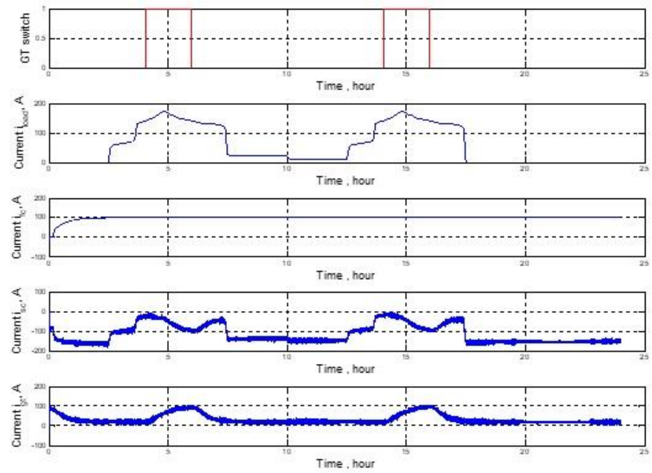


Figure 9. Results of the first load profile with fuel cell 100A and capacitor 100F

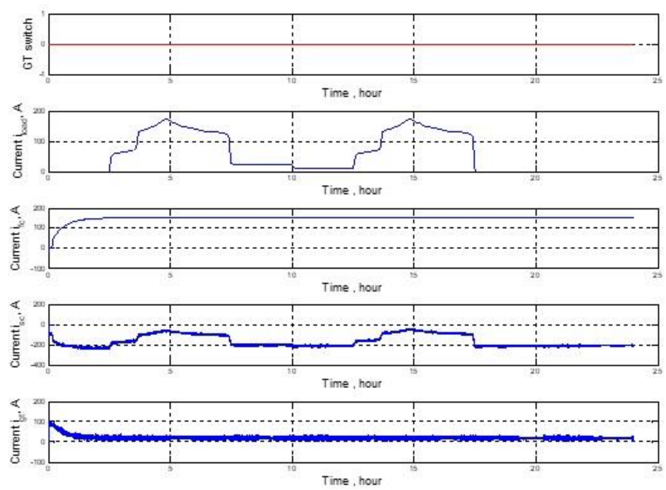
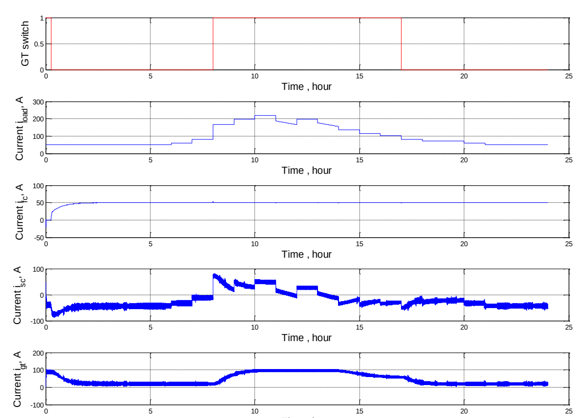


Figure 10. Results of the first load profile with fuel cell 150A and capacitor 100F



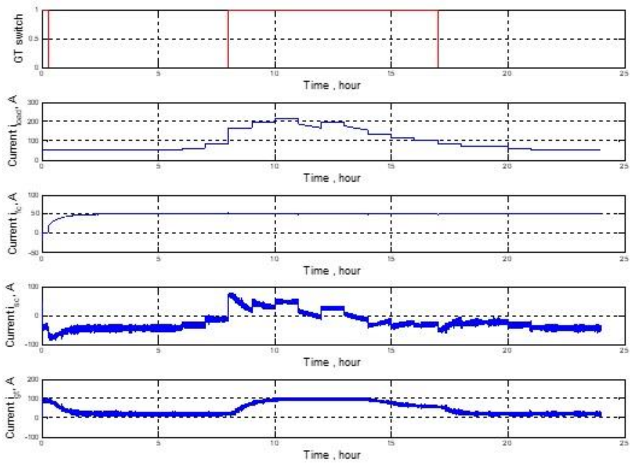
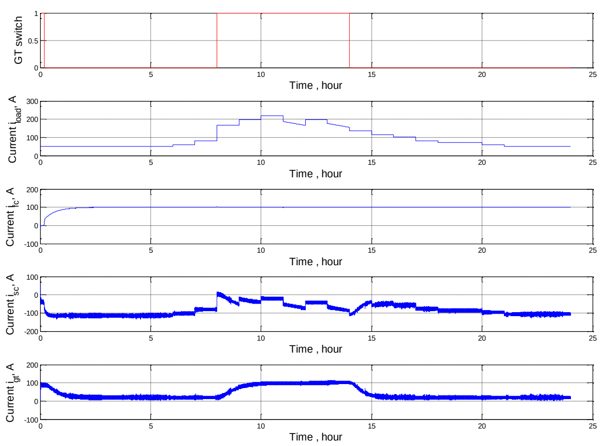


Figure 11. Results of the second load profile with fuel cell 50A and capacitor 100F



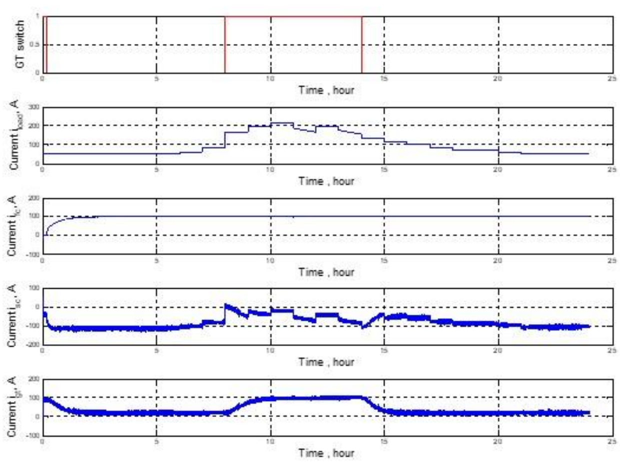
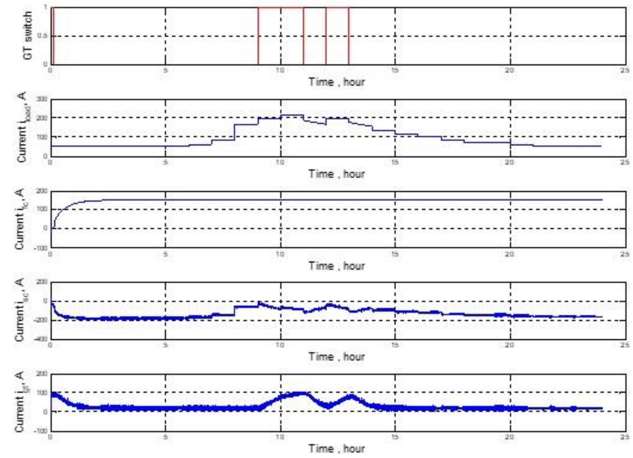


Figure 12. Results of the second load profile with fuel cell 100A and capacitor 100F



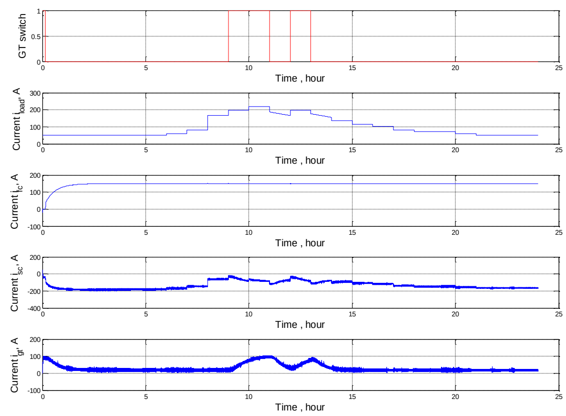


Figure 13. Results of the second load profile with fuel cell 150A and capacitor 100F

The basic idea of this research is to realize optimization procedure for reducing the capacitance of the capacitor and thus could reduce the cost of building a charging station for electric vehicles.

Results of the optimization with first load profile and capacitor limits $C_{\min} = 5, F\ C_{\max} = 100, F$. Finally, the optimization is started and the optimal value for C = 12.435 [F] is obtained (Figure 14 and 15).

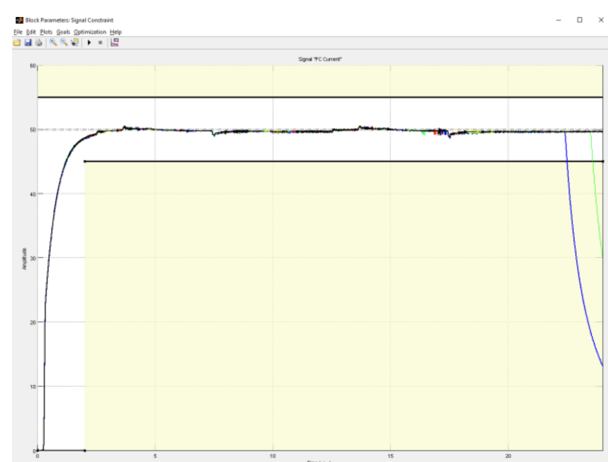


Figure 14. Graphical results of the optimization procedure for the capacitor of the first load profile with reference of the fuel cell 50A.

```
Optimization Progress

                                 max                  Directional  First-order
Iter  S-count       f(x)     constraint   Step-size   derivative   optimality
   0        1     1.65224         0
   1        5    0.812282         0         0.828       -0.828         0.454
   2        8    0.739045         0          1.01       -0.454        0.0872
   3       11    0.738669         0         0.239      -0.0872        0.0355
   4       14    0.738415         0         0.164      -0.0355        0.0173
   5       17    0.738164         0         0.157      -0.0173       0.00359
   6       20    0.738111         0         0.041     -0.00359       0.00149
Optimization terminated due to slow progress in parameter or objective values.
To optimize further, go to Optimization Options and decrease the parameter and/
function tolerances.

C =

   12.4350
```

Figure 15. Numerical results of the optimization procedure for the capacitor of the first load profile with reference of the fuel cell 50A.

Results of the optimization with second load profile and capacitor limits $C_{\min} = 1, F$ and $C_{\max} = 100, F$. The results of Figure 17 is simulated with the obtained optimal value for C = 3.1454 [F].

Figure 16. Graphical results of the optimization procedure for the capacitor of the second load profile with reference of the fuel cell 50A.

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Optimization Progress

                                 max                  Directional  First-order
Iter  S-count       f(x)     constraint   Step-size   derivative   optimality   Procedure
   0        1     2.56934         0
   1        6    0.763747         0          1.92        -1.92         0.109
   2        9    0.762029         0         0.116       -0.109        0.0382
   3       12    0.761261         0        0.0622      -0.0382        0.0174
   4       15    0.760354         0        0.0522      -0.0174        0.0134
Optimization terminated due to slow progress in parameter or objective values.
To optimize further, go to Optimization Options and decrease the parameter and/or
function tolerances.

C =

    3.1454
```

Figure 17. Numerical results of the optimization procedure for the capacitor of the second load profile with reference of the fuel cell 50A.

V. Discussion

Based on the analysis of the results of the different variants in the two selected load graphs shown in Figure 8 to Figure 13, it is found that increasing the fuel cell current reduces the use of the gas turbine, which is logical to provide the load assignment. In this way, if the load schedule is known (based on data or forecast), the requirements to the energy sources and storage element (supercapacitor) and to the system of power electronic converters, through which the energy flows are controlled, are determined.

The optimization of the value of the SC can decrease his price and the price for building the charging station. The usage of the FC and MT is significant cheaper, but can assure the necessary power.

For their autonomous operation is necessary to assure an element for energy storage. Actually, the applied structural solution used battery but one of the problems for their usage is the increasing price of rare-earth material for their production. Due to the reason that the FC and MT operate with natural gas and hydrogen can help decreasing of the harmful emission in comparison with conventional power sources. The transportation of natural gas is easily accessible and well-known. This type of hybrid system can assure autonomous power supply in the hard reach places, where there is no supply by the distributed grid. This solution also allows mobility of the entire system.

VI. Conclusions

In the current research a mathematical model of hybrid autonomous system is realized. The hybrid system is supplied by fuel cell, supercapacitor and a micro gas turbine. In this scenario the load profile are two electric vehicles: BMW-i3 and Nissan Leaf. The fuel cell maintains the constant current and when the charging current is not sufficient the supercapacitor and the micro gas turbine gives the necessary supplying power. The implementation of an autonomous charging station would significantly help to relieve the loads profile in the distribution grid. Also, it would be convenient for usage in hard-to-reach areas in emergency situations and loss of mains power. For these reasons, the research and implementation of such type of charging station would would be an advantage in the modern development of electronic and power systems. From the presented results it can be observed that the mathematical model is appropriate for this application.

A comparison of different values of the SC is presented. It can be observed that after the optimization procedure the system operates appropriate. The optimization of the process could decrease the expenses for investment in this project.

In further researches this type of charging station it can be updated with addition of the system for hydrogen production, which can increase the autonomy of the charging station.

NOMENCLATURE

Abbreviations

EV- electric vehicle
FC- fuel cell
MT- micro gas turbine
SC-supercapacitor
PV - photovoltaic
PMSM - permanent magnet synchronous machine
PMSG - permanent magnet synchronous generator
PWM – pulse width modulation
WG – wind generator
SoC- state of charge

List of symbols

d and *q* - physical quantities;
Rs - the stator resistance;
Ld and *Lq* - inductances of the d and q axis;
Lis – the inductance between the phases;
Lqs and *Lds* - the stator inductances;
Lid and *Liq* - the leakage inductances;
ψf - permanent magnetic flux;
ωe - electrical rotating speed;
EOC - voltage of the open circuit;
N - number of cells;
A - slope of Teifel;
i0 – current;
Td - time response of the system;
Rohm - internal resistance;
ifc - current of the fuel cell;
Vfc - voltage of the fuel cell.
c- molar concentration
Na - Avogadro constant
Temp - operating temperature of the supercapacitor
Ne - number of layers related to the Stern model
r - molecular radius related to the Stern model
R - ideal gas constant
ε_0 - permittivity of free space
ε - relative permittivity of material

ACKNOWLEDGMENT

This research was carried out within the framework of the project “Artificial Intelligence-Based modeling, design, control and operation of power electronic devices and systems”, КП-06-Н57/7/16.11.2021, Bulgarian National Scientific Fund.

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Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

B.G., G.V., P.S. and N.H. were involved in the full process of producing this paper, including conceptualization, methodology, modelling, validation, visualization and preparing the manuscript. Authorship must be limited to those who have contributed substantially to the work reported. All authors have read and agreed to the published version of the manuscript.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This research was funded by Bulgarian National Scientific Fund, grant number КП-06-ПН57/7/16.11.2021, and the APC was funded by КП-06-ПН57/7/16.11.2021.