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Cite as: AIP Conference Proceedings **2048**, 060027 (2018); https://doi.org/10.1063/1.5082142

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Mathematical Modelling of a Charge Station with Supercapacitor Energy Storage

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Abstract. The modelling and control of a DC-coupled hybrid system composed of a micro gas turbine and supercapacitor energy storage bank is presented in this paper. The supercapacitor is used for short power balancing in order to achieve constant power at the system output until the micro gas turbine reacts to the load change. The corresponding control system for power references setting and control of the converters has been developed. The hybrid system is modeled and implemented in MATLAB/Simulink. Simulation results demonstrate proper operation of the proposed hybrid system and its control – at the moment when an electric vehicle is plugged in to the system, the required power for fast charge is provided. In this way fast recharging of electric vehicles can be performed at remote gas stations without further reinforcement of the existing power distribution infrastructure.

INTRODUCTION

Nowadays, as a result of the growing number of electric vehicles (EV), the development of an appropriate infrastructure for their recharging is a raising concern. The standard charging of an EV can take up to 10 hours and provides a range of up to 200-300 km. Therefore fast chargers for EV have been developed in the recent years: in fast charge mode the EV battery can be fully recharged in under one hour, but require a power of up to 30kW for a single vehicle. In order to adapt the existing infrastructure for an increased number of EV and their usage for long distances, a possible solution is to implement fast charging stations in the gas stations. But simultaneous charging of multiple EV in fast charge mode is an important load for the grid which will require reinforcement of the distribution infrastructure [1-4]. Furthermore in some cases gas stations are in remote areas without connection to the distribution grid at all and are using internal combustion engine-driven generators. Generators driven by a small gas turbine and having a rated electrical power of up to several hundreds of kW are increasingly used for autonomous power supply in remote areas or for backup generators ensuring uninterruptible power supply of office or institutional buildings [5-10]. Micro Gas Turbines (MGT) are often preferred rather than diesel groups for autonomous or backup power supply because of their fast response to changes in the load and lower pollutant emissions than conventional internal combustion engine driven generators. The electrical efficiency of a micro gas turbine is up to 25% and by combined heating and power generation (CHP) the overall efficiency can reach up to 80-85% [8-11].

The implementation of EV fast chargers in remotely located gas stations can be done by using micro gas turbines for electricity generation. The time constant of a typical MGT by a step change in the load is in the range of 20-30 seconds. To remove such limitations in the dynamics of the power source, some form of storage system is necessary at the AC or DC bus to cope with instantaneous changes in power demand. In autonomous mode, this is critical in the case of sensitive loads, because micro-grids will be incapable of meeting load requirements if a storage system is not

Proceedings of the 44th International Conference on Applications of Mathematics in Engineering and Economics
AIP Conf. Proc. 2048, 060027-1–060027-7; https://doi.org/10.1063/1.5082142
Published by AIP Publishing. 978-0-7354-1774-8/$30.00

included [5-9]. Therefore the addition of a supercapacitor in the charge station is required in order to provide an energy buffer until the MGT output reacts to the change in the load.

The modelling of a hybrid charge station with micro gas turbine and supercapacitor short-term energy storage is presented in this paper. The proposed hybrid systems is composed of an MGT and a supercapacitor connected to a common DC bus through power electronic converters. At the DC bus is connected the EV fast charger and a three-phase inverter coupled to the same DC bus ensures the power supply of the AC loads located in the gas station.

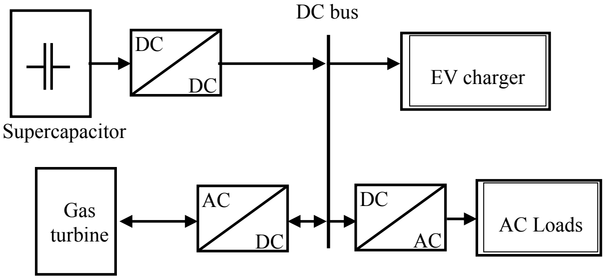


FIGURE 1. Structure of the studied hybrid system

MODELING OF THE SUPERCAPACITOR

The Electrochemical Double Layer Capacitors (EDLC) are often referred to as supercapacitors or ultracapacitors. Their structure and operation principle are well known and similar to all other capacitors. Although there is one difference that allows them to have a huge capacitance, compared to “common” capacitors. Both electrodes are made of porous substance submerged in liquid electrolyte and separated by an ion-permeable membrane (separator). Due to the large surface of the electrodes (1000-2000 m^2/cm^3) these capacitors have a capacitance up to several hundreds or even thousands of Farads. When voltage is applied from an external source, the ions are collected on the electrodes surface. The capacity of such capacitor can be as high as thousands of Farads [5]. They have high power density and exploitation life of millions of charge/discharge cycles which makes them very convenient for applications needing high power for short periods of time [5-11]. The last years, supercapacitors are subject to numerous researches for their use in hybrid systems with Renewable Energy Sources (RES), as well as with other energy storage technologies. In the hybrid system with RES, supercapacitors can compensate the power fluctuations from RES, which are due to the fast changing stochastic character of the primary source (wind or PV).

The advantage of supercapacitors is that they can be charged and discharged with a current hundreds of times greater than batteries without deterioration of their characteristics and shortening of their exploitation life. Also, supercapacitors have better energy efficiency: the energy stored in a supercapacitor is about 90% of the energy used for charging it and for the lithium-ion batteries his parameter is at a level of 70-80%.

On figure 3-A is presented the simplified equivalent circuit of a supercapacitor. In this circuit to the capacity C are connected an Equivalent Series Resistance (ESR) and Equivalent Parallel Resistance (EPR). ESR represents the operational losses inside the capacitor and EPR represents the self-discharge (leakage). When these parameters are determined, an approximation of real supercapacitor operation is achieved for short-term applications (<10s). In this study the simplified equivalent circuit is chosen because the supercapacitor is used for short term energy storage. The modeled capacitor has a capacity of 14 F and a nominal voltage of 400V. The values of ESR and EPR are 10 mΩ and 40 kΩ respectively.

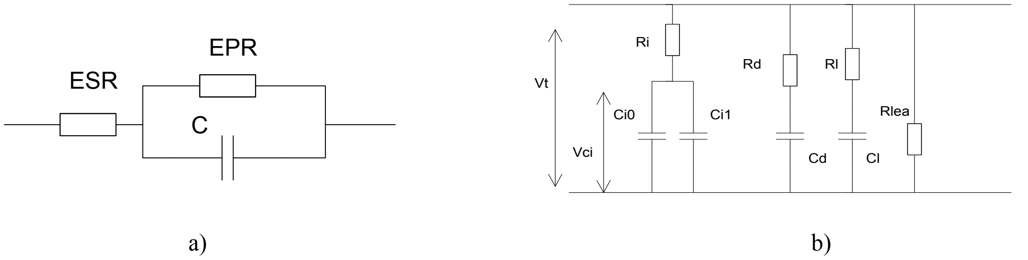


FIGURE 2. Simplified (a) and three-branch (b) equivalent circuit of a supercapacitor

However, for long-term energy storage applications a more precise model with three branches is also referred in literature [5, 8, 11]. This three-branch supercapacitor equivalent circuit is presented on Figure 3-b. In this circuit each branch has a different time constant. The first branch, containing *Ri* (immediate) and two capacitors (C_{io} and C_{i1}) characterizes the supercapacitor behavior for short term applications (from a few milliseconds to a few seconds). The second one (modeled by C_d and R_d) represents supercapacitor behavior in the time domain form a few seconds to a few minutes and the third one is for long-term (more than a few minutes). As on the simplified equivalent circuit, the equivalent parallel resistance R_{lea} represents the parallel resistance which causes the leakage (self-discharge) current.

MODELING OF THE MICRO GAS TURBINE

For this application, we have chosen a Capstone Micro C330 Turbine Generator is chosen [8-11]. The device is a recuperated single stage radial flow compressor and turbine coupled on the same shaft.

This MGT is composed of the following subassemblies a Gas Compressor (GC), Combustion Chamber (CC), a turbine, a Heat Recuperator (HR), a high-speed permanent magnet synchronous machine and two power electronic converters – a PWM-controlled rectifier and a three-phase inverter. The block diagram representing the structure of a micro gas turbine is represented in Figure 3. This model of Capstone MTG is powered by natural gas. The rotating components are mounted on a single shaft supported by air bearings. Air from the generator then flows into the GC where it is pressurized and forced into the cold side of the HR. Exhaust heat is used to preheat the air before it enters the Combustion Chamber and thus reduce fuel consumption by about 50 percent. Then, the CC mixes the heated air with fuel and burns it. This mixture expands through the turbine, which drives the GC and generator at a speed of up to 100-150 thousand RPM. The combusted air is then passed through a heat recuperator before being evacuated by the exhaust outlet. The mechanical force generated by the expansion of the burning air-fuel mixture drives a radial turbine mounted on the same axe with the inlet compressor and with a high speed permanent magnet synchronous generator (fig. 3). On some models the electrical generator can also be coupled to the main axe through a gearbox, but often it is directly coupled and its rotational speed can be as high as 200 000 RPM [9-15]. The generated high-frequency three-phase system is rectified and then converted to AC with frequency and amplitude conforming the load requirements or the grid in the case of a grid-connected application.

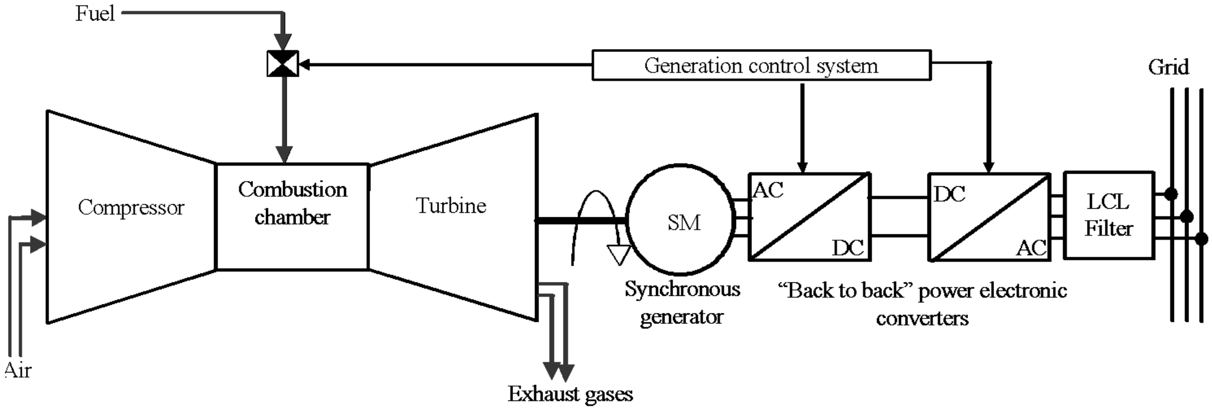


FIGURE 3. Structure of a micro gas turbine generator

The used High-speed Generator is a two-pole Permanent Magnet Synchronous Machine (PMSM) with a non-salient rotor. This PMSM generator is cooled by the air flow into the Micro-turbine, and the output of the generator is a variable-voltage system, variable-frequency AC power at a frequency of up to 1,600 Hz. At this speed the machine develops its ratedpower output of 28kW electrical and its rated terminal line-to-line voltage which is 400 V. A micro-turbine requires about 15-20 seconds for a 50% change in power output. The figure 9 shows the Capstone M330 Micro Turbine responses to a step change in the fuel valve [7].

The dynamic modelling and simulation of the Micro-turbine have been discussed in details in many sources [12]-[16]. Nikkhajoei and M. R. Iravani have proposed a model for the MTG based on the Nern's non-linear long term model of the Gas Turbo Generator [14]. In [13], the authors developed a generic model of a grid-connected micro-turbine converter. In [15], a linearized model of the micro-turbine was adopted and compared to a first order transfer function. In [12], the authors were interested in analyzing thermodynamics and the electromechanical stability of micro turbines.

After analysing these modelling approaches, for this study a simple first order adaptive model is chosen. This is the model used in this work. Table I presents the identified rise time value of output power. In figure 4 is presented the MGT model power output – with dashed line is depicted the power reference (power demand from the loads) and with a solid line is the MGT model power output [10, 11, 15].

TABLE 1. MTG time constant by a step change in the load

P **ΔP**	5000	10000	15000	20000	25000	28000
-28000	50	50	50	50	50	50
-15000	52	52	52	39	26	18
-10000	44	44	28	12	15	16
-5000	36	28	22	12	12	10
0	37	25	24	15	13	9
5000	38	22	26	18	14	8
10000	38	38	40	42	23	12
15000	38	38	38	30	21	16
28000	49	49	49	49	49	49

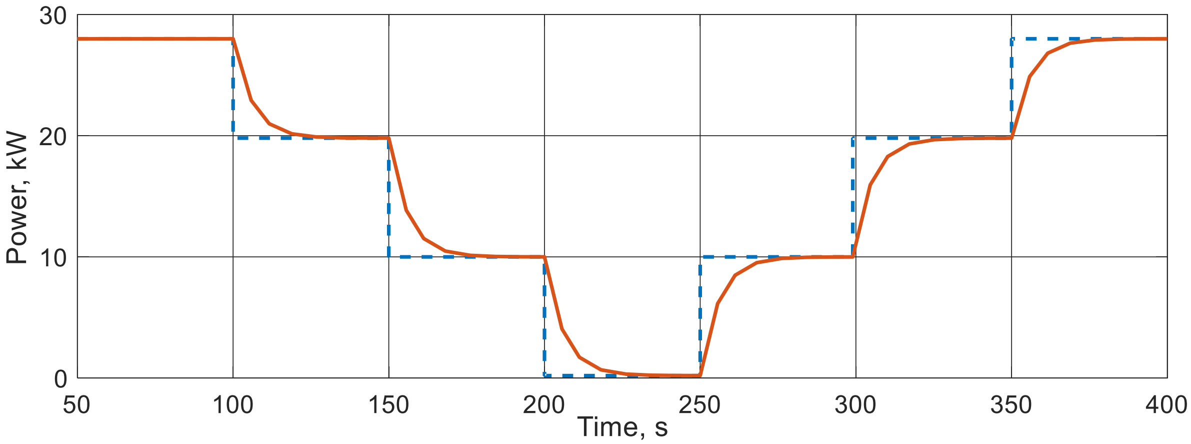


FIGURE 4. Power reference (dashed line) and model output (solid line) of the micro gas turbine moDel

MODELLING OF THE CONTROL SYSTEM

The power flows diagram from the sources (the micro gas turbine and the supercapacitor) to the DC bus is depicted in figure 5. The power flows diagram is expressed assuming that the losses in the power converters are neglected. The power delivered to the DC bus is the sum of the power produced by the MGT and the supercapacitor. At the other hand, the DC bus feeds power to the local AC loads (through a three-phase inverter) and to the EV fast charger (through a DC-DC converter). The power balancing equation can be expressed mathematically as follows:

$$P_{AC\_loads} + P_{EV\_Charge} = P_{DC} = P_{MGT} + P_{SC} \tag{1}$$

Assuming that the AC loads power and the power required for charging the EV are known, the power reference for the micro gas tubine P_{MGT_ref} can be expresed:

$$P_{MGT\_ref} = P_{AC\_loads} + P_{EV\_Charge} \tag{2}$$

As the time constant of the micro-gas turbine is in the range of 20-50s, until the given output power reference is reached the supercapacitor delivers the required power. The power reference for the supercapacitor is equal to:

$$P_{SC\_ref} = P_{AC\_loads} + P_{EV\_Charge} - \hat{P}_{MGT} \tag{3}$$

Where $\hat{P}_{MGT}$ is the measured electrical power output of the micro gas turbine. The control system structure according to the above equations is depicted in figure 6.

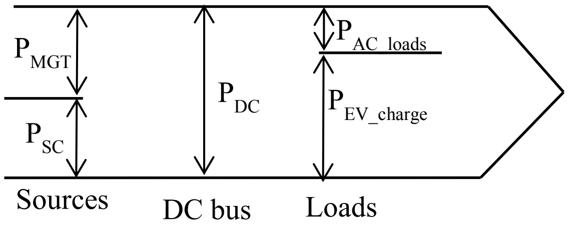


FIGURE 5. Diagram of the power flows in the studied system moDel

The balancing condition in this autonomous system implies that the consumed power has to be generated by the sources. The purpose of the supercapacitor is to provide a short term energy storage in order to compensate the relatively slow MGT response time. When the MGT reaches its new generatoin set point, the control system recharging of the supercapacitor also starts in order to be ready to perform power compensation in the next cycle – when another EV will be plugged in for recharging.

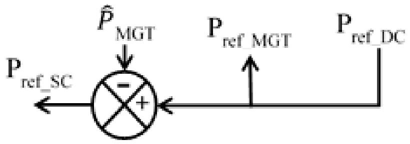
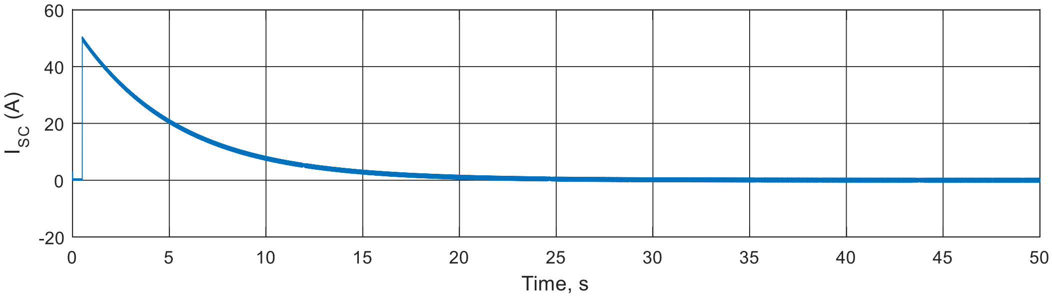


FIGURE 6. Calculation of the MGT and SC power references

SIMULATION RESULTS

The system model is implemented in the Matlab/Simulink environment. The simulation is performed with a step signal for the DC bus power reference from 0 to 20kW, simulating the arrival of an electric vehicle at the charge station. The objective of this test is to prove that the supercapacitor is able to ensure power balancing until the micro gas turbine has reached the given power reference. The current and voltage of the sueprcapacitor bank are presented in figure 7. From the simulation results it is visible that the sueprcapacitor compensates sucessfully the micro gas turbine delay and constant power is delivered to the DC bus (figure 8).



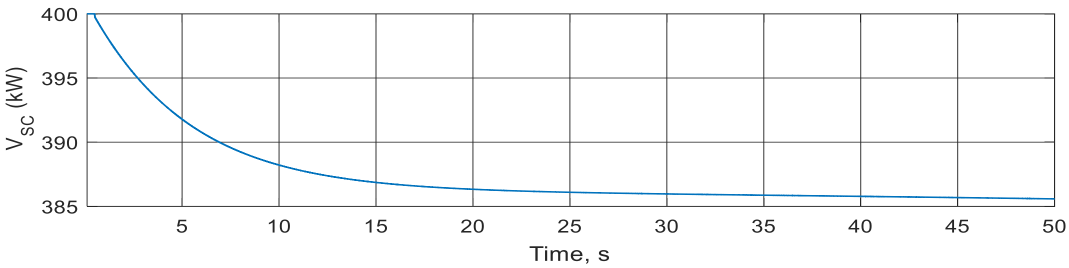


FIGURE 7. Simulation results: Curent and voltage of the Supercapacitor bank

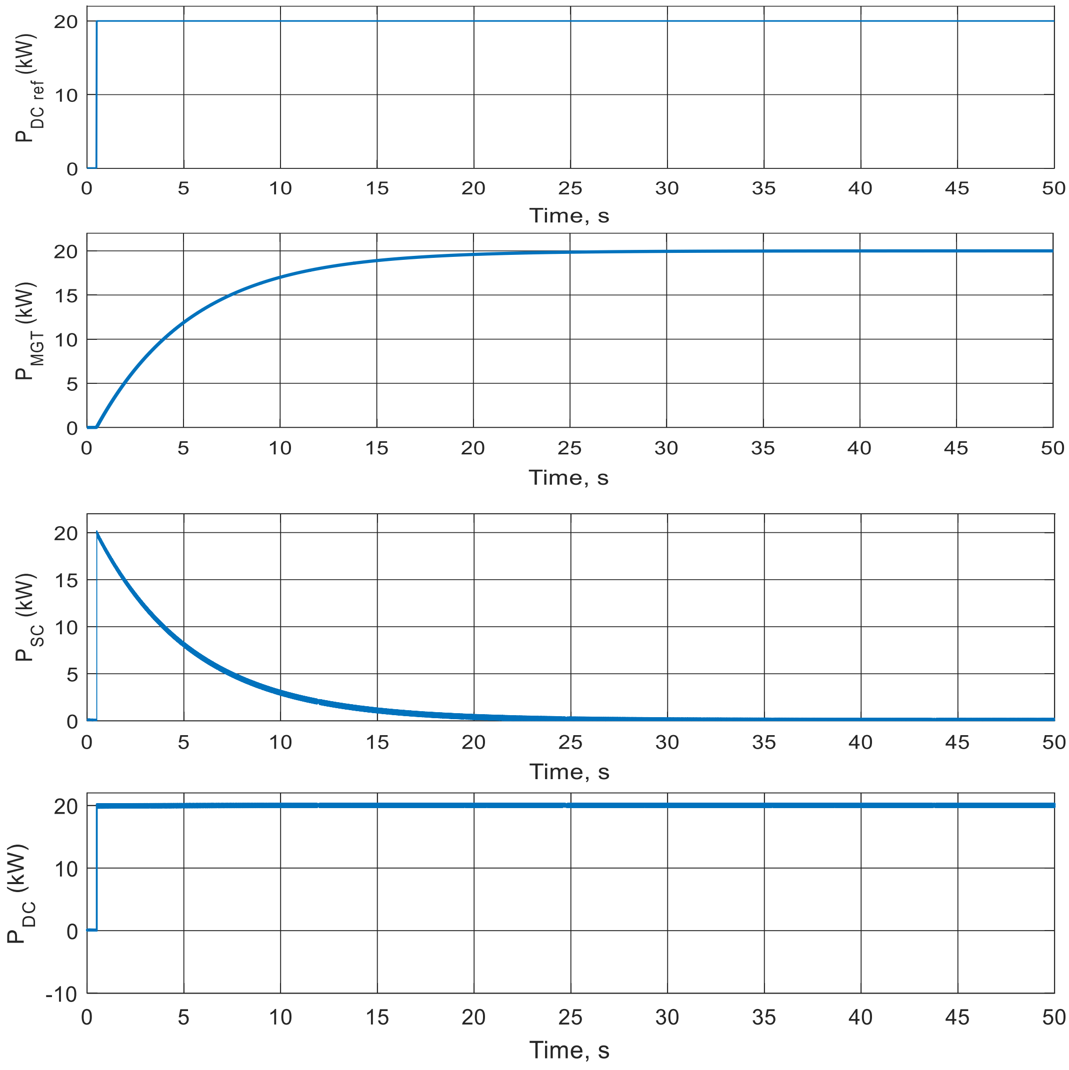


FIGURE 8. Simulation results: power reference of the DC bus, active powers supplied by the supercapacitor, the micro gas turbine and total power delivered to the DC bus

CONCLUSION

The modelling and control of a DC-coupled hybrid system composed of a micro gas turbine and supercapacitor energy storage bank is presented in this paper. The supercapacitor is used for short power balancing in order to achieve constant power at the system output until the micro gas turbine reacts to the load change. The corresponding control system for power references setting and control of the converters has been developed. The hybrid system is modeled and implemented in MATLAB/Simulink. Simulation results demonstrate proper operation of the proposed hybrid system and its control – at the moment when an electric vehicle is plugged in to the system, the required power for fast charge is provided. The supercapacitor supplies the necessary power until the micro gas turbine reacts to the load change and raises its power output to the new setpoint. In this way fast recharging of electric vehicles can be performed at remote gas stations without further reinforcement of the existing power distribution infrastructure.

ACKNOWLEDGMENT

This research is funded in the framework of project „Gestion intelligente des flux énergétiques dans des micro- et nano-réseaux" funded by Agence Universitaire de la Francophonie and the Bulgarian National Fund for Scientific Research.

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