HYBRID FUEL CELL POWERED CHARGING STATION FOR URBAN SUPERCAPACITOR BUSES

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***Abstract* – design, development and construction of fast charging station prototype based in fuel cells for supercapacitors propelled city bus. The charging time should be enough to fully recharge the pack in order to allow the bus to reach the next station [1] but not too long to maintain the passengers comfort. In order to perform fast charging of a bus the charger delivers around 2.2kWh of energy in 60-90 seconds. Due to fuel cell characteristics DC-DC converter with buffer is required to ensure proper usage.**

INTRODUCTION

Future intercity transportation will rely on electronic motors instead of Internal Combustion Engines (ICE) thank to low level of emission and noise. The common ways to propel electric bus are: Constant connection to grid and onboard energy storage devices [2]. While constant connection to grid determines ahead the route of the bus and forces it to move in exactly same route every time. Power source based onboard energy storage device can alternate it course depends on the capacity of the storage device. This paper describes the use of onboard energy storage device based on SuperCapacitor (SC). The reasons for choosing SC over regular batteries will be described later. Problems regarding dealing with fast charging issues [3] of SC, replacing the energy source from regular grid connection to Fuel Cell (FC)' FC's IV curves [4], response time and purging will discussed later. By using FC the emission level will drop and grid connection will become needless. Some problem can be solved by proper algorithms and remaining problems can be solved by DC/DC converters.

I. Super capacitors

Transporting passengers should be as quickly and reliable as possible. Decreasing weight and volume of the energy source is crucial for achieving common wide electric propulsion. Batteries possess high energy density meaning it can supply energy it possess low power density (As seen in Figure 1). High energy density means that power source can supply energy for long period of time contrary to high power density that can supply high amount of energy for short period of time. The bus must departure as quickly as possible from the station so the energy storage device must be able to withstand high charging power rate (94kW). SC withstands high power charging rate as explained above, in order to deliver 2.2kWh the average time for SC charging is around 90 seconds during this time the passengers will board to the bus. On the contrary, batteries charging will take few hours which make it not feasible in case of ongoing routine bus. Another aspect is the cycle life of the power source, average cycle life of battery is approximately 500 rounds. SC on the other hand is more than 10,000. Frequent charging and discharging emphasis the crucial of cycle life of chosen power source, degrading in capacitor/batteries performance can damage the motor due to high current drawn from the power source. Taking this parameters into account indicate that use of SC is the best solution for transportation. Using this type of energy storage device demands an adjustment of hardware and infrastructure, for example: fast charging station. First demand is charging rate below the SC peak charging rate, second demand is transferring energy without stressing the power source (grid or FC).

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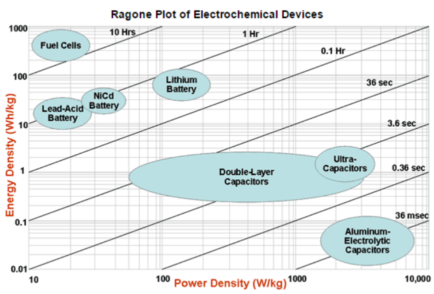

Figure 1 – Ragone chart

II. Fuel cell

Supplying energy to the charging station can be done using grid or FC. While grid connection requires AC-DC converstion, FC implementation requires DC-DC converter based on boost topology [5] . Fuel cell has high energy density (around 1kwh/kg seen in Figure 1) . Output of FC is DC and its voltage is relativily lower than the maximum voltage of the SC when it charged making DC-DC converter mandatory in order to complete the charging of the SC. Another problem relies in the charcheristic of FC shown in Figure 2, the IV curve of FC point that increased load lowers the terminal voltage of the cell. [6] In case of Constant power charging (CP) the voltage can drop to a level where the converter wont be efficient (due to drawn of high currents), acording to that charging method must be adjusted to the FC type. Regular operation of FC require ejaculation of the inner cell reactants, this processes called "purging" during the purge, power cannot be drawn from the FC due to shortcut phenomona (current climbes to peak values and very low voltage output). Compare to other energy sources like batteries or capacitors FC can't deliever high power [6] instantneously. The preffered method to draw energy from FC is by fixing it on one point of operation, when applying this method the FC will deliever power at the same rate for long period of time. Constant power withdrawn from the FC will able to exploit the advatages of FC as high energy source .

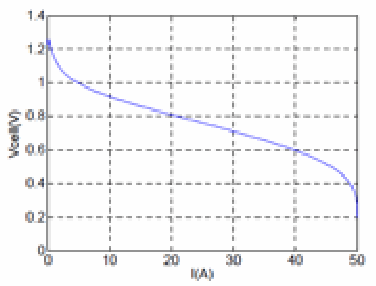

Figure 2 – FC IV curve

III. Overall considerations

The following SC bus energy storage will be further considered: 600V ideal SC pack (internal and wiring resistance are disregarded for simplicity during initial design) with 75% useable energy (pack voltage is allowed to reduce down to half rated voltage, i.e. 300V) of 2kWh. Assume that the average SC round-trip efficiency is 90%, hence in order to allow the energy storage to provide 2kWh of energy, the charger would deliver 2.2kWh.

Moreover, the following nominal traffic schedule will be considered: buses arrive to each station once in 6 minutes (360 seconds) and the charging time is 1.5 minutes (90 seconds). Assume that the service average power consumption (lightning, signaling, cooling etc.) of a charging station is P_S = 1kW and charging efficiency is 95%. Note that in the worst case, 2.2kWh should be provided during 90 seconds, resulting in average charging power of ~88kW.

IV. Charging methods

There are two main methods of charging SC, each consisting of 2 stages: constant current (CC) → constant voltage (CV) and constant power (CP) → constant voltage (CV). Note that the first stage of both methods is the dominant one. The CV stage is required to perform residual charging due to the fact that when the SC terminal voltage reaches its rated value during charging, its internal capacitance voltage is lower because of the voltage drop on the equivalent series resistance (ESR). Since increasing the terminal voltage beyond its rated value has an adverse effect on the device cycle life, at this point charging process enters the CV stage, where terminal voltage is kept at its rated value and the current decays exponentially while the internal capacitance voltage increases. The charging is usually terminated when the current decreases below a predetermined value.

Analyzing the CC and CP stages, the following is revealed. In terms of device efficiency, CC charging is optimal (ESR losses are minimal). In order to deliver 2.2kWh to the above mentioned energy storage in 90 seconds, the CC stage charging should be performed at ~198A. Note that since the capacitor voltage will be increasing from 300V to 600V, the charging power will increase linearly from ~59kW to ~118kW. As to CP charging, it is performed at the average rate of 88kW and the ESR losses are higher than in the CC case. This is explained by the high initial charging current of ~293A when the capacitor voltage is 300V, reducing to ~146A when the terminal voltage reaches its rated value. Comparing the two charging modes it may be concluded that during CC stage, charging power reaches higher values than during CP stage (118kW versus 88kW); however, the maximum current during CP stage is higher than during CC stage (293A versus 198A).

To conclude, each charging mode has its advantages and disadvantages. One possible solution is combining both modes, performing CC charging when the terminal voltage is low to reduce ESR losses and then switching to the CP mode to limit the charging power. This allows rated current-power tradeoff. An example hybrid mode charging envelope is shown in Figure 3. The CC charging is performed at ~212A during 45 seconds, bringing the terminal voltage from 300V to ~461V; then, CP charging is carried out at 97.5kW during another 45 seconds to bring the SC to 600V. The relevant signals are shown in Figure

4. Note that this is just an example (CV mode time is disregarded); obviously, optimal charging current and power ratings should be carefully determined.

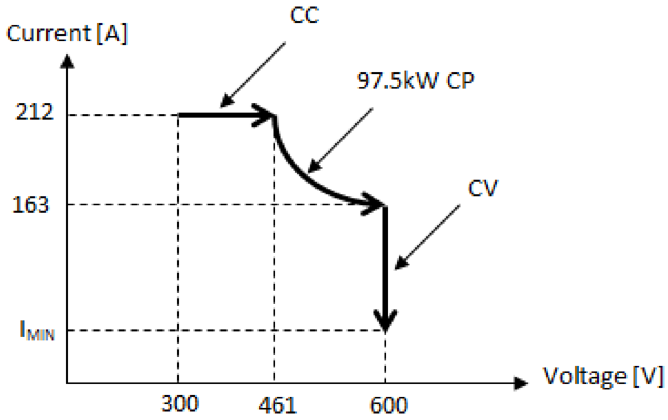

Figure 3 – charging envelope sequence example

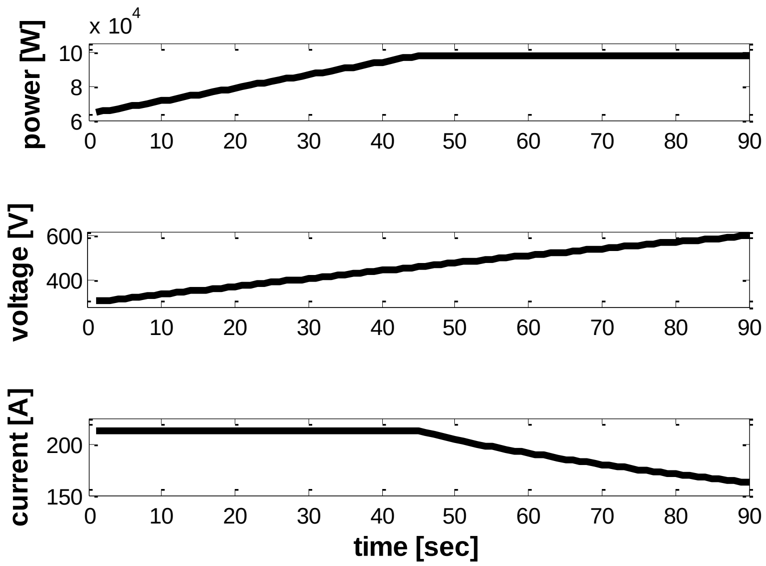

Figure 4 – charging process signals

The charging station considered here is fed by a 123V (orion by nuvera 25KW), DC fuel cell system. Two main topologies will be considered next: without and with an energy buffer.

It is important to note that the FC voltage should be allowed to vary by **- 50%** from its rated value. At the same time, the station should be able to create DC voltage between 300V and 600V. Obviously, boost operation must be supported to cover all cases. The boost converter will determine the voltage across the capacitor in order to imply CP mode while the capacitors are charging. [5] [6]

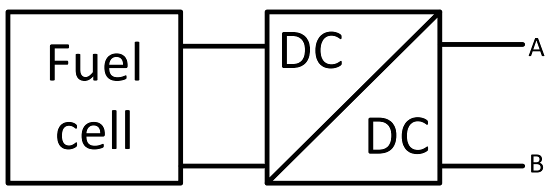

Figure 5 – Bufferless topology

The power stress on the FC during CP charging is shown in Figure *6* Note that while the peak power is 94kW, the average power is only 24kW, However since no buffer is present, both conversion stage and the FC must be able to withstand the worst case loading. Considering that FC is not able to support high load changes due to its characteristics [6], buffer less topology won't be sufficient. The purging sequence will damage the CP mode due to voltage drop, so instantaneous power source is needed to store some energy to allow constant power delivering.

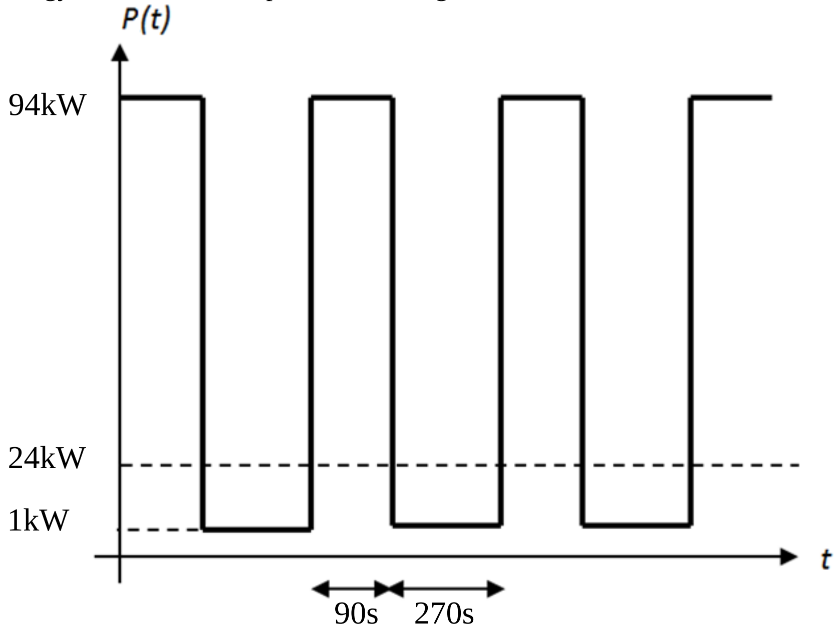

Figure 6 – FC effort during CP mode

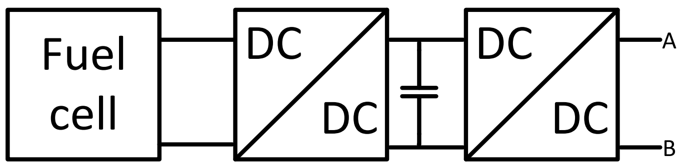

Figure 7 – Buffered topology

Presented in Figure 7 buffered topology [5] fuel cell connected through boost converter in order to raise the voltage from 123V to 800V and maintaining CP mode while drawing average power from the FC (24kW) [6] . The FC will charge the capacitor with the amount of energy before transferring it to the load while it connected (70kW for 270s) [7]. Because the minimum voltage of the bus's SC will be approximately 300V another DC-DC converter is needed to provide current limit while energy is transferred. While the entrance level of the intermediate capacitor is boost, the exit level will be buck to assure controlled charging in order to prevent damage.

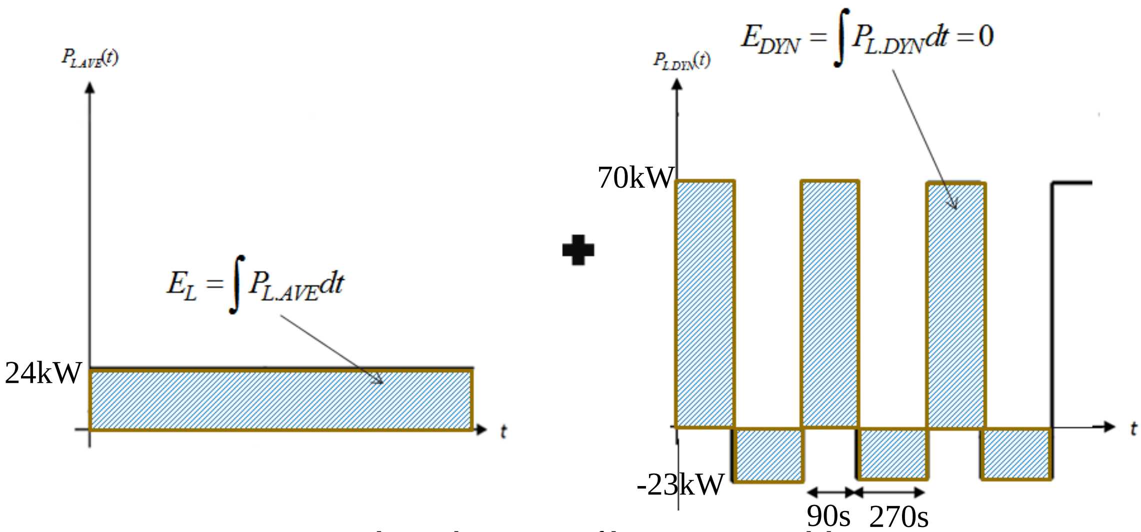

Figure 8 - Splitting the power profile into average and dynamic parts

Figure 8 (left section) presents the effort from the FC, as presented. CP mode in 25kW rate is applied while the station is working, meaning slow charging of the capacitors in the exact energy needed in order to support the bus charging [8]. When bus enters to the station, high power charging begin – Dynamic part of the charging. Power is transferred from the SC of the station to the SC on bus at 70kW rate (right section presents the effort on the SC).

Conclusion

Proving probability of the system done using MATLAB simulation software. Under the assumptions that load behavior is similar to pulse train with predetermined pattern (power command). Described in *Figure 9* the charging station of the SC based bus, power demand is determined from the main controller. The following system presented here implement CP charging on the buffer capacitor (intermediate capacitor). While the bus acts like constant power consumer in high rate of charging (94kW).

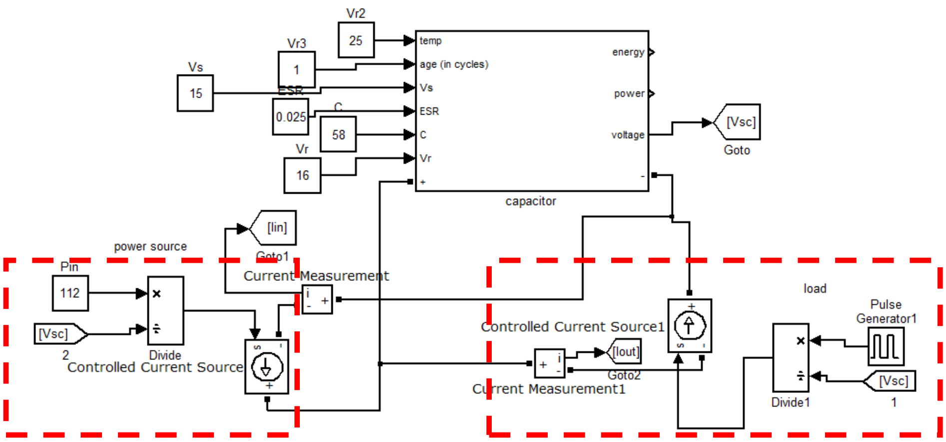

Figure 9 – simulation description of charging station

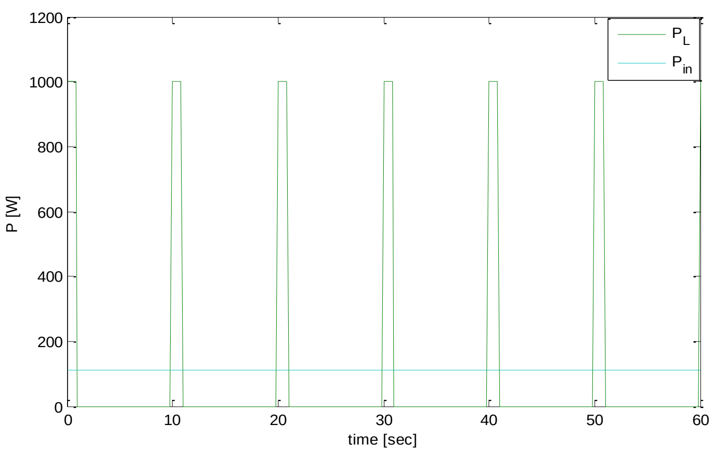

Figure 10 – constant power charging and pulse discharging

The simulation succeeded to deliver high power from the stimulated capacitor to the bus as described in *Figure 10*. Pin is the CP charging on the capacitor, PL is the charging rate of the bus. Due to limitations of equipment maximum power rate is 1 kW while the CP withdrawn from the FC is 100W. Comparison between simulation and actual system will be done approximately in the same rate. Prototype was built with the following components: 1 KW DC load, 200W Horizon FC, 58F Maxwell SC.

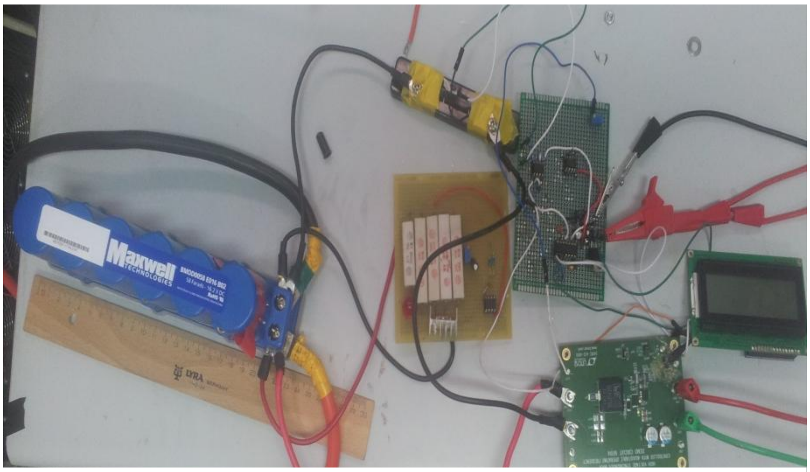

Figure 11 – downscale prototype of charging station

The prototype is fed by 200W horizon FC in CP mode for 15 seconds in 100W charging rate and stimulates the time between bus arrivals. Immediately after bus arrival high power charging begun in 1kW rating for 2seconds as shown in Figure 12.

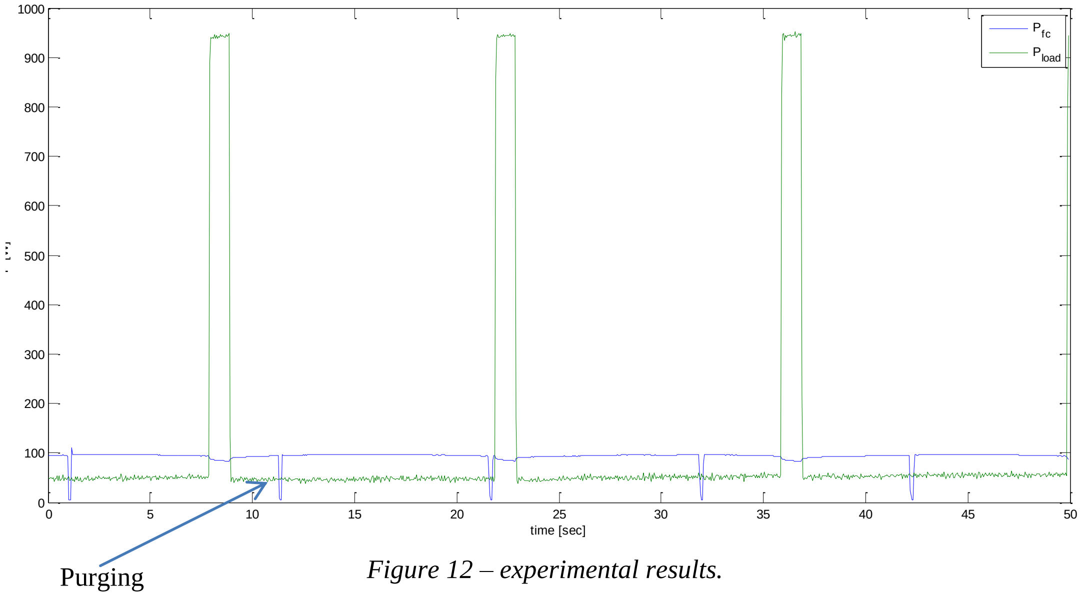

Figure 12 – experimental results.

Notice that despite the purging sequence CP charging doesn't disturbed, power flowing to the load (intermediate capacitor) keeps running.

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