Characteristics of an electronic converter for supercapacitor charging

Dimitar Arnaudov, Nikolay Hinov, Ivan Nedyalkov

In the following article a converter, providing mutual work between photovoltaic system and energy storage elements have been studied. The converter provides the management of the energy flows to/from the supercapacitor battery. Simulation and experimental studies of the power part of the system has been made. The main characteristics of the studied converter are presented.

Характеристики на електронен преобразувател за заряд на суперкондезатор. (Димитър Арнаудов, Николай Хинов, Иван Недялков). *В работата е изследван преобразувател, осигуряващ съвместната работа на фотоволтаична система и елемент за съхранение на енергията – суперкондензатор. Той управлява енергийните потоци от и към суперкондезаторната батерия. Проведени са симулационни и експериментални изследвания на силовата част от системата. Построени и представени са основните характеристики на изследвания преобразувател.*

Introduction

The supercapacitors are perspective elements for energy storage thanks to their advantages, compared to the classical elements for energy storage [1, 2]. Due to the relatively high prices and low gravimetric energy density, the supercapasitors must be used together with batteries. Different algorithms for management of energy flows between energy source, battery and supercapacitor are possible [3], [4], [5].

For studying the management algorithms of energy flows, via PV, battery and supercapacitor, a test bench of a PV system has been created [6].

The target of the following research is converter, providing charging and voltage balancing across supercapacitors [7].

1. Bi - directional converter.

To use supercapacitors in a system for energy storage, it is necessary to use bi-directional converter. The converter is necessary to manage the energy flow from/to the supercapacitor. The bi-directional converter is made of two unidirectional converters. The energy transfer from the power source to the supercapacitor is done, by using Resonant Inverter with Voltage Limitation Over the Commutating Capacitor (RIVLOCC). For the energy transfer from the supercapacitor to the load is done by using a classical Boost DC-DC converter [8].

In the following article, a charging converter will be studied. The block diagram of a bi-directional converter is shown on figure 1.

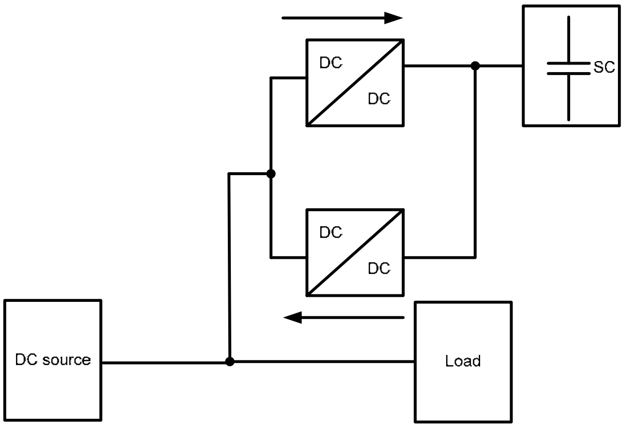

Fig.1. Block diagram of the proposed system.

2. Studying of the converter for charging and voltage balancing over series connected supercapacitor cells.

The power circuit of DC/DC-1 converter is shown on figure 2. The converter is composed of:

- Half-bridge RIVLOCC with divided power source;
- The AC circuit is composed of the following resonant elements: C_k, C_{k1}, L_k and inverter transformer (one primary winding w_1 and six secondary windings $w_2 – w_7$.)

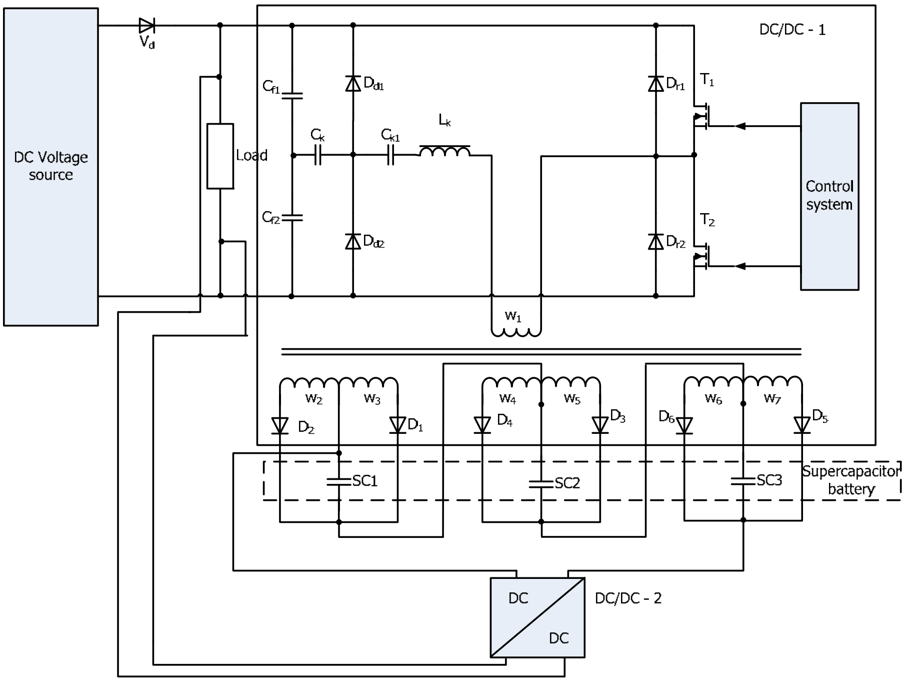

Fig.2. Proposed circuit for charging and balancing.

The supercapacitor battery is made of series connected supercapacitors – SC1, SC2 and SC3. The rectifiers, connected to the secondary windings of the inverter transformer charges the individual cells.

One of the advantages of the converter is voltage equalization over series connected supercapacitor cells [9]. The capacity of cell 1 is 20% lower than cell 2. The capacity of cell 3 is 20% bigger than cell 2.

Simulation studies of the circuit from figure 2 have been made, by using LTSpice [10]. Figure 3 shows the waveforms of current through transistor T$_1$ – Id(T1). The used simulation model of the transistors is with internal reverse diodes.

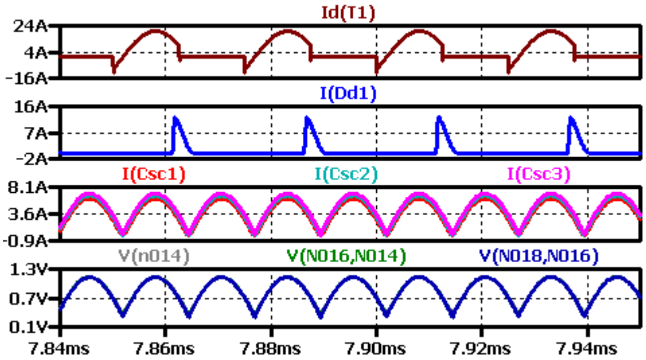

Fig.3. Current and voltage in the begging of the charge

The rest waveforms are: current through limitation diode D$_{d1}$ – I(Dd1); current trough supercapacitor SC1 – I(Csc1), SC2 – I(Csc2), SC3 – I(Csc3) and voltage across the supercapacitor SC1 – V(N014), SC2 – V(N016, N014) and SC3 – V(N018, N016).

From the waveform of the voltage it can be seen that despite different values of the capacity of the supercapacitors, the voltage over them is almost equal. This is one of the features of the circuit. The values of the current through the elements changes during the charging. Another advantage of the proposed circuit is the limitation of the maximum values of the current through the elements, which values are highest at the beginning of the charge of the supercapacitors. Other techniques for inrush current limiting are given in [11].

Figure 4 shows the waveforms of the voltage across the resonance capacitor C$_k$ - V(N006, N005); current through diode D$_{d2}$ - I(Dd2) and the current through inductor L$_K$ – I(L1).

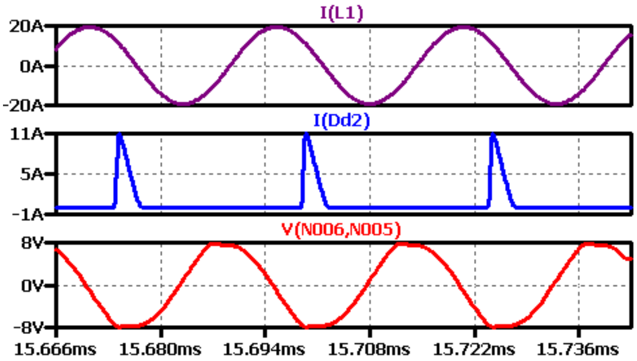

Fig.4. Current and voltage in the diagonal of the half-bridge.

From the waveforms it can be seen that, when the value of the voltage over C_k reaches the value of ± $U_{d/2}$, the limitation diode turns on and the recharge of C_{k1} continuous.

According to the stage of the charging regime, the limitation diode turns on at different moments.

When reaches a certain value of the voltage across the charged capacitor, the voltage over Ck cannot exceed ± $U_{d/2}$ and the limitation diodes do not turn on.

In the studied case, RIVLOCC works in above the resonance regime. Which of the two diodes will turn on earlier – reverse or limitation depends on the parameters of the circuit and the voltage over the charged elements.

The characteristic of the studied converter depends on:

- Hesitation coefficient – k;
- Frequency coefficient – ν;
- Voltage, to which the supercapacitors are charged;
- Ratio p between C_k and C_{k1}

$$p = \frac{C_{k1}}{C_k}, \quad (1)$$

where C_k and C_{k1} are the resonance capacitor.

A simulation study of the DC/DC - 1 converter from figure 2 has been made during the charging of the supercapacitors. During the process of charging, for different values of the voltage over the supercapacitor cell - SC1, the measured parameters are:

- Maximum value of the current through the transistor;
- Maximum value of the current through the reverse diode;
- Maximum value of the current through SC1;
- Average value of the current through the SC1;
- Average value of the consumed current;
- Maximum current through limitation diode.

The characteristics of the parameters above were built in relative units. For obtaining the results in relative units, the measured values are divided into the parameter I_{sh}

$$I_{sh} = fC_kU_d, \quad (2)$$

where f is the driving frequency, C_k is the resonance capacitor with voltage limitation over it, and U_d is the power supplying voltage.

The research has been made for two values of the p ratio. In the characteristics the solid line is for p = 0.044 and the dotted line is for p = 0.066.

Figure 5 shows the characteristic of the consumed current in relative units.

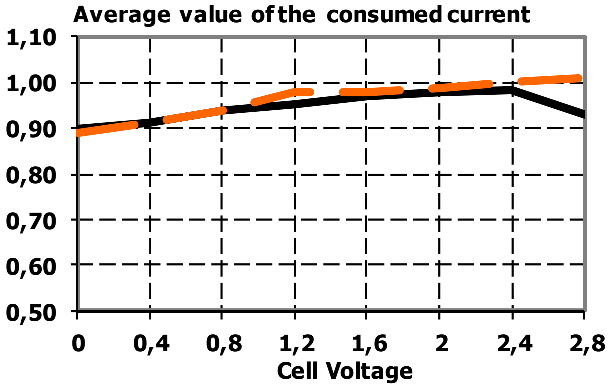

Fig.5. Characteristic of the average value of the consumed current

From the characteristic, it can be seen that the consumed current is almost constant. A bigger change appears when the limitation diodes are turned off. The consumed current is continuous with small ripples, which leads to evenly loading of the DC power supply. This is especially important for supplying devices from photovoltaic systems and fuel cells.

Figure 6 shows the characteristic of the maximum value of the current through transistor T_1, in relative units.

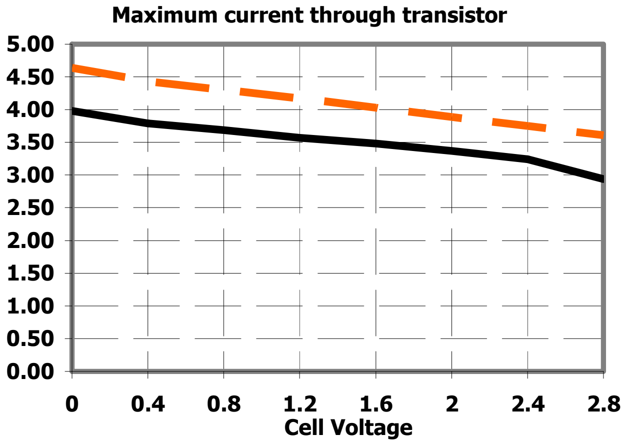

Fig.6. Maximum value of the current through transistor T_1.

From this characteristic, the range of the amendment of the current in the process of charge of the SC can be seen. This would help when we choose the transistor.

Figure 7 shows the characteristic of the maximum value of the current through the reverse diodes, integrated in the transistors when charging the supercapacitor. This characteristic can be used for choosing the working regime of the Resonant Inverter with Reverse Diodes (RIRD). For better energy efficiency of the circuit it is necessary to use working modes with less conducting times of the reverse diode in the beginning of the charge. In addition, it is desirable to provide conducting of the reverse diodes during the whole charging process, aiming zero switching. At bigger values of the p ratio, the range of amendment of the current is bigger.

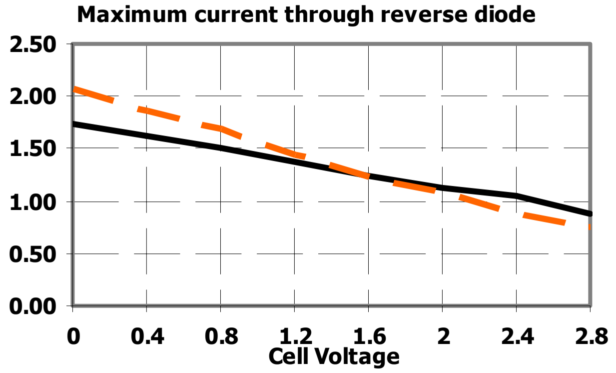

Fig.7. Maximum value of the current through reverse diode.

Figure 8 shows the characteristic of the maximum value of the current through the limitation diodes, during charging.

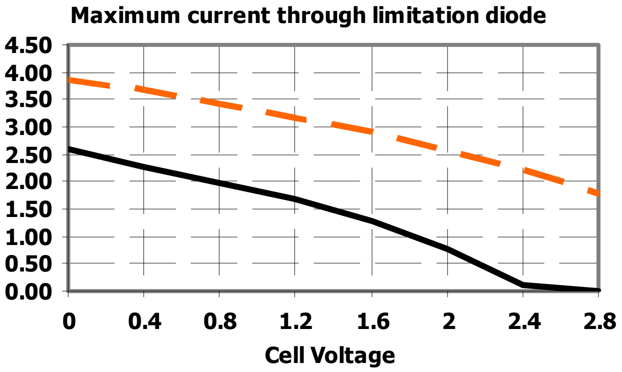

Fig.8. Maximum value of the current through limitation diode.

When the value of the p factor is p = 0.0444 and U_{sc} = 2,5V, the maximum value of the current reaches zero. So the limitation diodes turn off. After they are turned off, the characteristic of the circuit is the same as the classical RIRD, working in above the frequency mode. This characteristic can be used for determination of the values of the elements in the resonant circuit to obtain limitation modes, during all the time of the charging. The characteristic would help for choosing of the working mode of the converter for efficient use of the switching elements.

Figures 9 and 10 show the characteristics of the maximum value of the charging current through SC1 and the average value of the charging current through SC 1.

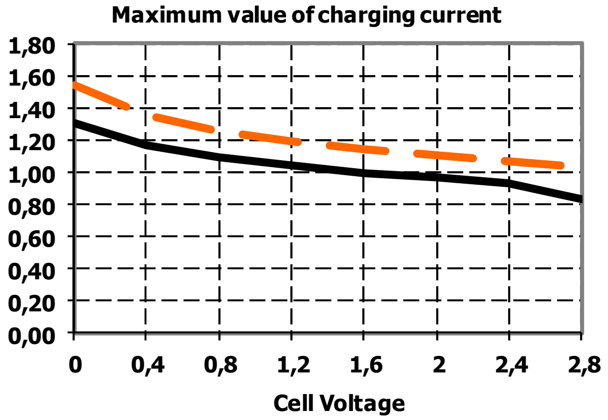

Fig.9. Maximum value of the charging current through SC1.

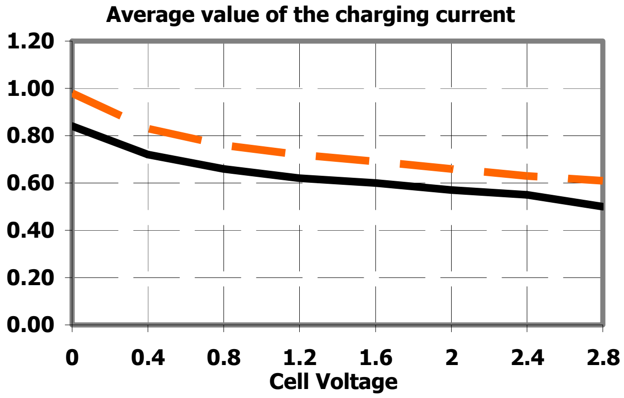

Fig.10. Average value of the charging current through SC1.

These characteristics can be used for choosing the working mode of the converter, such that the process of charging does not exceed the maximum value of the current through the supercapacitor, given by the manufacturer.

The characteristic from figure 10 can be used for evaluation of the instantaneous value of the power, by which the converter charges the supercapacitor.

3. Studying of a converter for charging and voltage balancing over series connected supercapacitor cells, by using CL – filter on the rectifiers.

To charge the supercapacitor cells with constant current, instead charging with pulse current, the circuit on figure 11 is proposed. The outputs of the rectifiers are connected to CL – filters.

Figure 12 shows the waveforms of: current through the rectifier diodes D_1 and D_2 – I(Diz1) and I(Diz2), current through SC1 – I(Sc1), current through

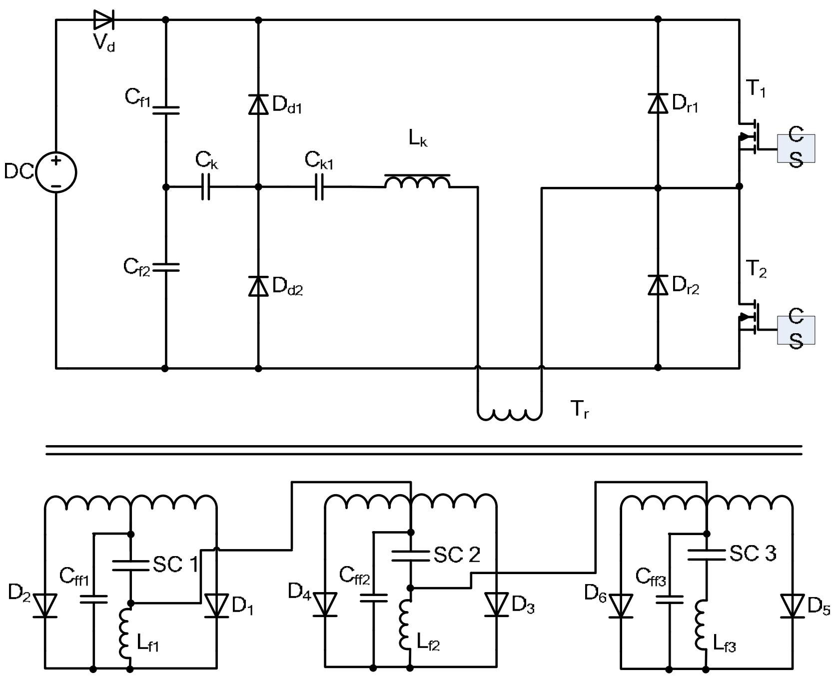

Fig.11. Proposed circuit for charging with constant current and voltage equalization.

filter capacitor C_{ff1} – I(Cff1), consumed current from DC power supply – I(V1). As it can be seen from the waveform of the consumed current, it is continuous, like it was mentioned in paragraph 2.

From the waveform of the current through the charging capacitor SC1 it can be seen that it is smoothed. Its average value is equal to the sum of the average value of the current through the two rectifier diodes. The value of the current through SC1 is:

$$I_{sc1} = \frac{2I_{2m1}}{\pi} = 0.637 I_{2m1}, \tag{3}$$

where I_{2m1} is the maximum value of the current through the rectifier diode D_1

On the other hand the maximum value of the current through the primary side winding of the inverter transformer is:

$$I_m = n(I_{2m1} + I_{2m2} + I_{2m3}), \tag{4}$$

where n is the transformer ratio of the inverter transformer. I_{2m1}, I_{2m2}, I_{2m3} are the maximum values of the current through the rectifier diodes.

The maximum values of the current through the primary winding of the inverter transformer I_m depends on:

- Hesitation coefficient – k;
- Frequency coefficient – ν;
- Ratio p between C_k and C_{k1}

Figure 13 shows the waveforms of the current through the rectifier diode D_1 – I(Diz1) and the voltage over it – V(N013, N014).

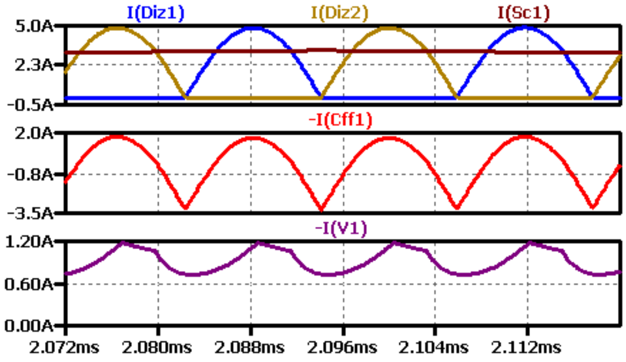

Fig.12. Current through the elements during the charging.

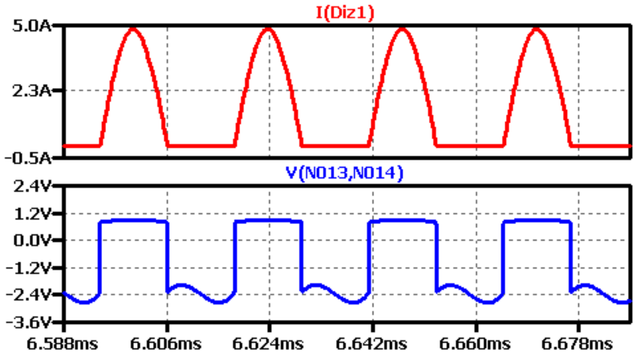

Fig.13. Current and voltage of the diode D_1.

The behavior of the circuit of the figure 11 is the same like the circuit of the figure 2. Therefore, this circuit has the same characteristics like these from figures 5 to 10.

4. Experimental studies.

For conducting of the experimental studies of the circuit from figure 2, a test bench has been developed. For the management of the converters and testing different management algorithms of the energy flows, a virtual instrument has been developed, by using the software – LabView. The virtual instrument is described in [6].

For the management of the studied circuit, shown on figure 2, a new virtual instrument has been developed. The chassis NIcDAQ and the developed virtual instrument are used to manage the converter. The front panel of the developed virtual instrument is shown on figure 15.

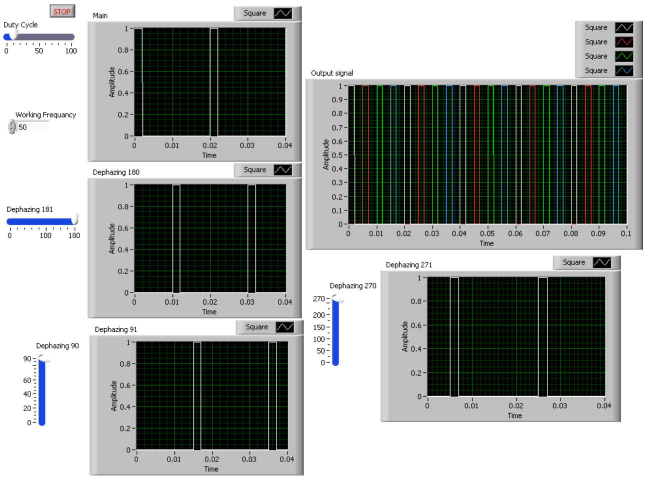

Fig.15. Front panel of the developed virtual instrument.

On the front panel, the input controls are used for managing of the driving frequency and phase shitting between the control pulses. The graphical indicators are only used for representation of the control pulses.

Figure 16 shows the block diagram of the virtual instrument. The functions of the blocks are:

- Block 1 – represents the input controls, by which we can manage duty cycle, control frequency and phase shitting between the control pulses. These controls are connected to the relevant inputs of the virtual generators;
- Block 2 – these are the generators of pulses. With them, we can set signals with different forms, amplitude, frequency, phase etc. There are two ways of setting the parameters: fixed and by using input controls, like in our case. In this case they are only used as generators of rectangular pulses;
- Block 3 – these blocks converts the signals from analogue to a string of 0 and 1;
- Block 4 – this is a graphical representation of the module NI9401 - TTL outputs, connected to DAQ chassis. The used TTL outputs are from 1 to 4 and they are used for management of four transistors. The control pulses at the TTL output are shifted relatively to one another. For the management of DC/DC – 1 converter from figure 2, we use only 2 outputs.

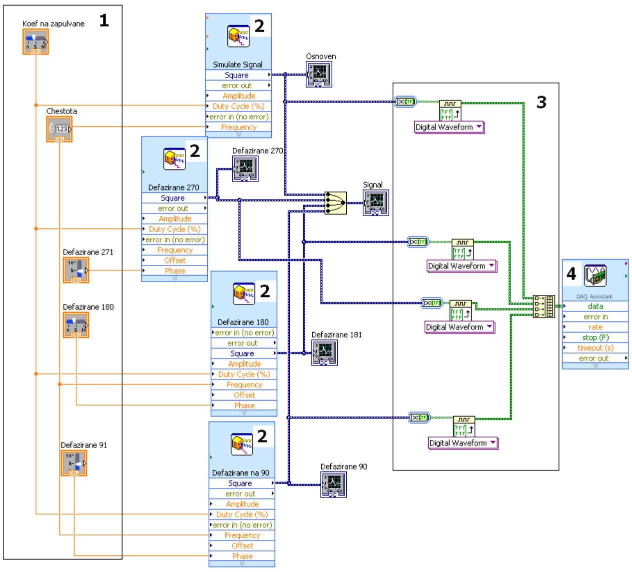

Fig.16. Block diagram of the virtual instrument.

Experimental studies with the proposed circuit and the developed control system have been made. The results from the experimental studies of the proposed circuit, confirms the simulation studies. The proposed virtual instrument allows realization of different principals of operation, which can be used for evaluation of its benefits and disadvantages.

Conclusion

1. The circuit of the converter for the management of the energy flows at charging, of series connected supercapacitor cells, has been developed. First, the circuit charges the supercapacitor cell with the lowest voltage over it. This is one of the necessary conditions for the realizing of the proposed management algorithm of the energy flows. After voltage equalization over the supercapacitor cells, the circuit charges all cells simultaneously.

2. Using a CL – filter in the circuit from figure 10 provides charging with constant current. The CL – filter does not change the principal of operation of the RIVLOCC

3. The obtained characteristics of the current through the elements allow the capability of evaluating the qualities of the proposed circuit. In addition, they can be used for basic rations for designing of the proposed circuit.

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