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High Voltage Supercapacitor Energy Storage Protection

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Abstract

Protection of high voltage supercapacitor-based energy storage is considered. The proposed scheme of high voltage supercapacitor battery is developed on the basis of conventional protection schemes of high voltage AC capacitor batteries. Both normal and abnormal mode of high voltage supercapacitor-based energy storage are investigated by the means of computer modeling. It is shown that proposed protection is capable to detect outage of single supercapacitor unit under the given supercapacitors parameters scatter.

Keywords: High voltage supercapacitor battery, energy storage, protection, computer simulation, voltage dip.

I. INTRODUCTION

Poor power quality leads to losses from 0.2 to 0.4% of GDP in different countries but main losses are caused by voltage dips and short-term interruptions in all cases [1]. If losses from dips and short-term voltage interruptions are caused by malfunctions of the control systems microcontrollers, then standard low-voltage UPS is the solution of the problem. However, there are a number of applications where energy consuming devices must also be supplied by electricity without interruption. These include mainly powerful motors of various precision metalworking machines, electric drilling rigs, etc. Power supply interruption of these loads leads to braking of electric motors and their jamming or defects in produced products. Commonly automatic transfer switches are used for this purpose. But when the main and backup power sources are various substations of a single electric network, even using high-speed thyristor static switches cannot provide the guaranteed elimination of interruptions. This occurs due to voltage decreases in the entire electrical network for a short circuit. A radical way to solve this problem is to use energy storage load as a backup power source.

This article discusses the device described in [2], which uses a high-voltage supercapacitor battery as the energy storage device. Such a solution requires almost no maintenance compared to Li-on batteries on the one hand and does not require a DC/DC converter necessary to connect a battery of low-voltage supercapacitors on the other hand.

The paper is organized as following. Chapter 2 provides brief information about the design and main parameters of the whole device. Chapter 3 describes high-voltage supercapacitor battery based energy storage. The proposed protection approach is considered in chapter 4, while chapters 5 and 6 contains computer modeling results and conclusions accordingly.

II. ACTIVE POWER FILTER WITH THE ABILITY OF ACTIVE POWER OUTPUT CAPABILITY DESIGN

The concept of MV active power filter with the ability of active power output capability as an extended function was developed [2]. Scheme of this device is shown in the figure 1, while its main parameters are described in table 1. Discussed device contains modular multilevel voltage source converter (MMC VSC) and supercapacitor based energy storage. The converter includes six arms grouped into three phases. Each arm includes reactor and a number of identical full-bridge IGBT submodules connected in series. All three phases of the converter are connected to the DC voltage poles coupled with energy storage.

Table 1. Power Conditioner Specifications

Parameter	Value
Rated AC Voltage	6.0 kV
Rated power	6.0 MVA
Number of submodules in arm	10
Rated SM voltage	1200 V
Rated energy storage capacity	9.0 MJ
Rated DC voltage of energy storage	9.6 kV
Peak active power	3.0 MW
PWM switching frequency	1000 Hz
Arm reactor inductance	5.0 mH

Most of the time described power conditioner act as active filter compensating imaginary power of load connected in parallel with it. Power conditioner starts to supply active power to sensitive load during deep voltage sag, momentary

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or instantaneous interruption after islanding them from the main grid.

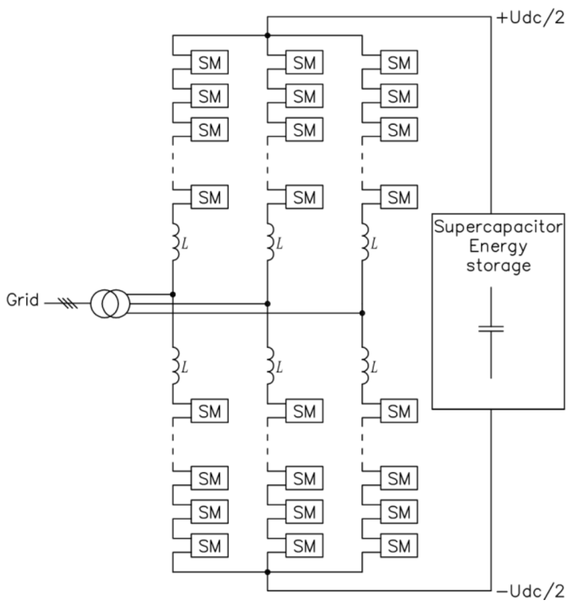
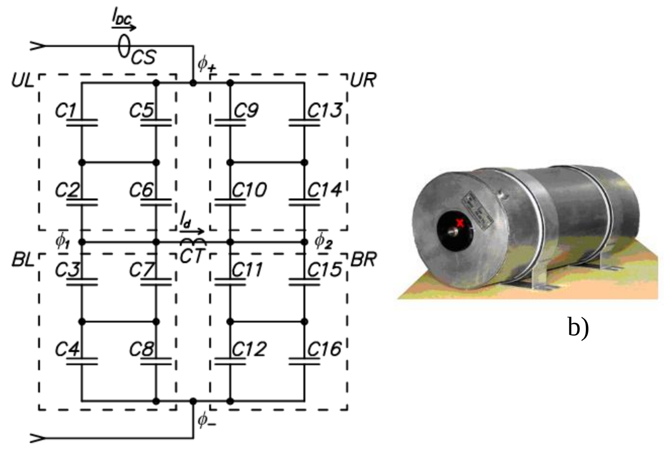


Figure 1. Converter scheme

III. HV SUPERCAPACITOR BASED ENERGY STORAGE SCHEME

A simplified diagram of a high-voltage battery of a supercapacitor energy storage device is shown in Figure 2a, where the current sensor for measuring ES current I_{DC} is denoted CS and CT is a current transformer for measuring current I_d in the diagonal of the bridge formed by the blocks UL, BL, UR and BR. Supercapacitors C1-C16 in this figure are shown conventionally.



a)

Figure 2. Supercapacitor based ES.

a) Simplified scheme b) Supercapacitor unit

Optimal parameters of HV supercapacitor based ES was calculated under phase current constraints [2]. To match the required parameters, a serial connection of 14 levels is required, while each level combines 8 supercapacitors units (Figure 2b) connected in parallel. The parameters of a supercapacitor unit are shown in table 2. So actually the supercapacitor battery is divided into 4 equal blocks UL, BL, UR and BR so each of them consist of seven floors connected in series, in each of which four unit supercapacitors are connected in parallel.

Table 2. Supercapacitor unit parameters

№	Parameter	Value
1	Rated voltage	700 V
2	Rated capacitance	0,5 F
3	Equivalent resistance	0,5 Ohm
4	Initial voltage	700 V
5	discharge voltage	350 V
6	Weight	40 kg
7	Diameter	0,2 m
8	Length	0,6 m

IV. PROPOSED PROTECTION APPROACH

It is known that a damaged supercapacitor goes into an open circuit state [3], which will lead to overcurrent of supercapacitors connected in parallel with it. The proposed high voltage protection approach is based on the known method for detecting a malfunction in the AC capacitor battery that utilizes the fact that the current I_d of the diagonal of the bridge is proportional to the current I_{DC} of the supercapacitor energy storage device and the degree of imbalance of the bridge according to the equation:

$$I_d = I_{DC}\left[\frac{Z_3}{Z_1+Z_3} - \frac{Z_4}{Z_2+Z_4}\right],$$

where Z_1, Z_2, Z_3 and Z_4 are the equivalent impedances of UL, BL, UR and BR blocks accordingly. In the general case, the degree of unbalance of the bridge can be caused by both the spread in the parameters of individual battery cells and the failure of single supercapacitor units. Without loss of generality, we can assume that the largest unbalance current in a supercapacitor battery with zero failed units corresponds to the case when in the UL and BR blocks all elements have the maximum positive deviation of capacitance within the tolerance, while in the BL and UR blocks all units have the maximum negative deviation of capacitance within the tolerance. Analytical dependences of the superior magnitude of the unbalance current I_d on the error eps of the parameters of individual supercapacitors at zero number of failed unit N0 and one failed unit N1 are shown in Figure 3, where the curve N1 corresponds to the mode of transition of any one element to a gap in the UL or BR block for seven floors connected in series, four elements connected in parallel.

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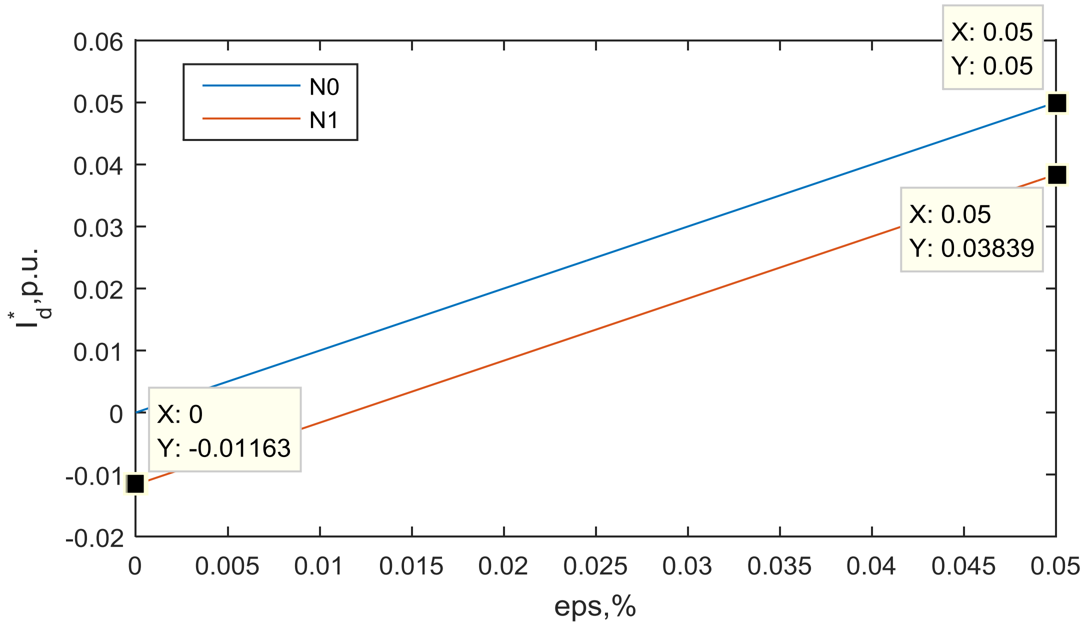

Figure 3. Analytical dependence of unbalance current on battery parameters

The dependencies shown in Figure 3 demonstrate that the failure of a single supercapacitor unit leads to 1% unbalance current under zero initial unbalance in the battery. But in some cases of initial unbalance due to the spread of parameters, a failure of an single unit can even decrease unbalance current in the diagonal of the bridge. Therefore, it was decided to use the deviation of the relative unbalance current value of the diagonal of the bridge as a factor in identifying a malfunction, instead of its absolute value.

A feature of high voltage supercapacitor battery for energy storage should be noted, namely in a buffer mode of operation when stored energy is constant the mean value of current I_d is almost zero, but is containes high frequency component caused by PWM of VSI. A computer modeling experiment was conducted to evaluate the ability of proposed protection approach to detect failures of supercapacitor units. Block-scheme of the algorithm implementing the proposed approach is shown in figure 4, where moving average over an interval multiple of the PWM period is denoted «mean»; «LPF» is a first-order low-pass filter with a cut-off frequency of 25 Hz; «HPF» is a first-order anti-aliasing filter with a cutoff frequency of 40 kHz and «Fm» is normalized measure of unbalance current.

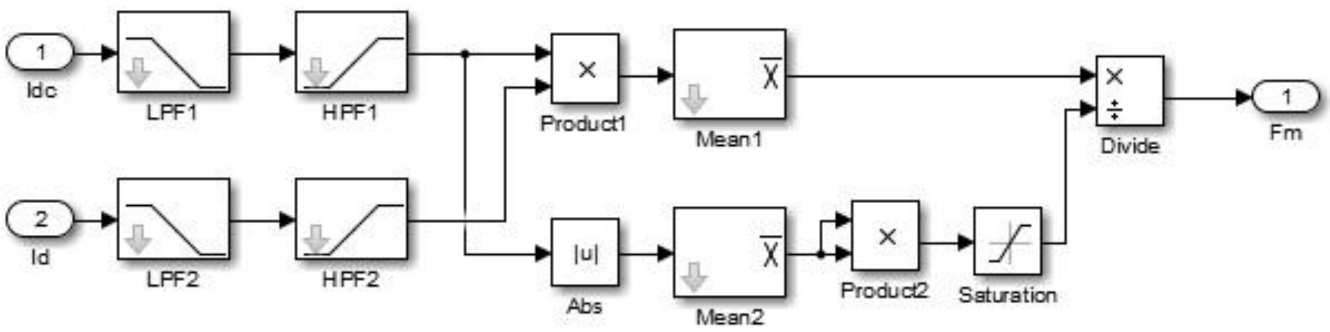

Figure 4. Block-scheme for calculation of normalized measure of unbalance current

When conducting a numerical experiment, the following tasks were set:

1. Verification that in case of failure of one supercapacitor, the proposed criterion makes it possible to detect a change in the current of the bridge diagonal with a tolerance of ± 5% in the parameters of individual supercapacitors.
2. Verification that the sensitivity of the method can be increased when a test effect on the drive is formed when a high-frequency current I_{DC} is forcibly generated with an amplitude comparable to the charge / discharge current.

V. COMPUTER MODELING

MATLAB Simulink was used for computer modeling the electromagnetic transient of high voltage supercapacitor based energy storage and MMC VSC. The Simpowersystems standard blocks were used to simulate the voltage converter and the high-voltage supercapacitor energy storage. Simulink standard blocks were used to simulate the control system. Implicit Euler scheme with fixed step time equal to 5 µs was used was used for solving differential equations.

The same distribution of supercapacitor unit parameters as in the previous chapter was used for modeling both normal and abnormal modes of operation of a high-voltage supercapacitor battery energy storage.

The simulation results are presented in figures 5-8. Figure 5 shows energy storage current I_{DC}, unbalance current Id and normalized measure of unbalance current Fm. These graphs correspond to the buffer operation mode of the drive, when the average current value at the industrial frequency period is stabilized at the zero value, and the high-frequency components are determined by the PWM converter. A supercapacitor unit fails in the UL block at instant 0.2 seconds fails causing the unbalance current to change and shift the normalized measure Fm accordingly. Thus simulation results agree with the analytically obtained results. In particular, in the absence of any faulty supercapacitors units in the battery and a given distribution of their parameters with an accuracy of 5%, the current in the diagonal of the bridge in the pre-fault mode is higher than in the post-fault mode, provided that all single supercapacitors in the UL and BR units had the maximum negative deviation resistance within an error of 5%, and in blocks BL and UR all elements had a maximum positive deviation of resistance within an error of 5%. The guaranteed change in the criterion Fm in case of failure of one supercapacitor is 0.009.

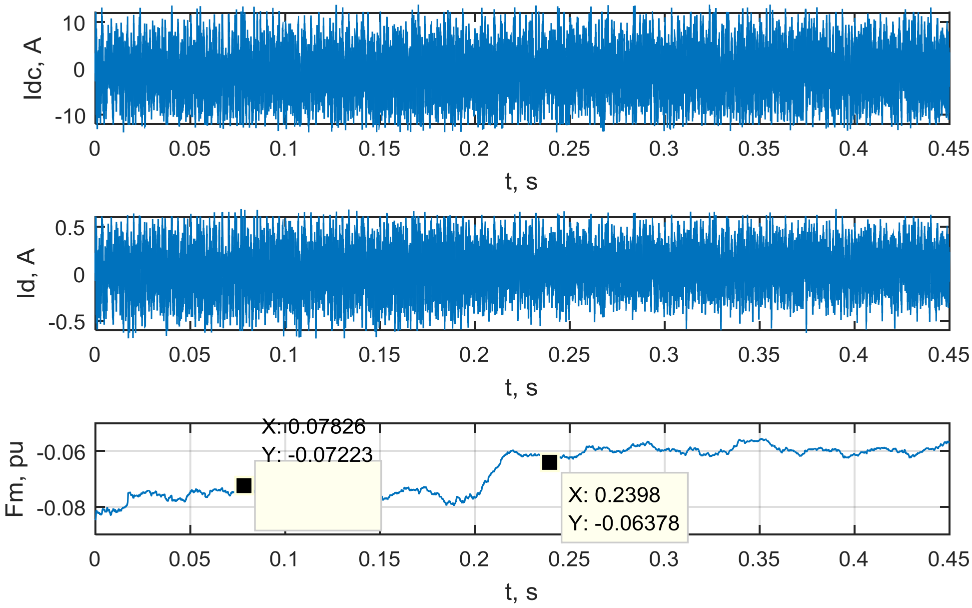

Figure 5. HV supercapacitor ES battery parameters in buffer mode

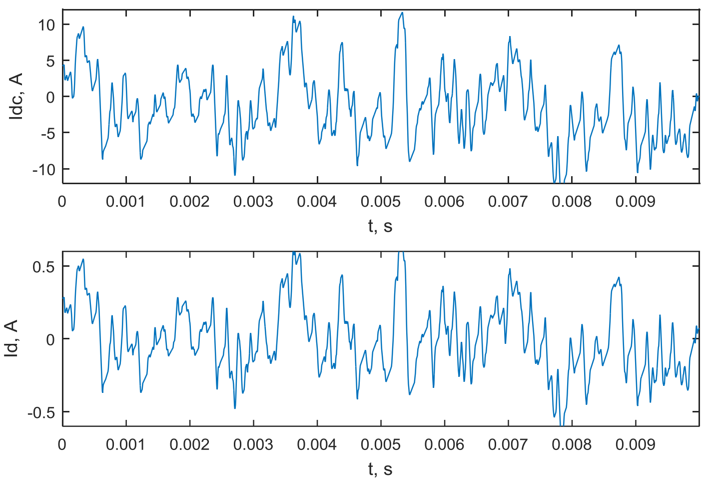

Figure 6. Scaled time segment of figure 5

The detection of changes in the criterion Fm is complicated by the presence of random deviations from the average value, which is due to the superposition of measurement noise on non-periodic signals of I_{DC} and I_d currents (Fig. 6) when the device is operating in buffer mode.

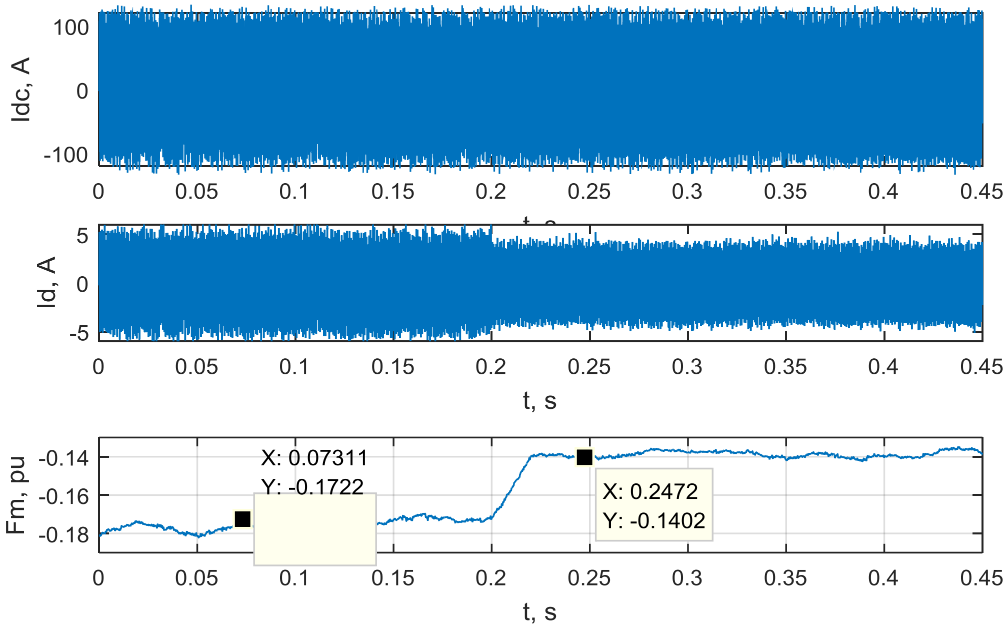

Figure 7. HV supercapacitor ES battery parameters in self-diagnosis mode

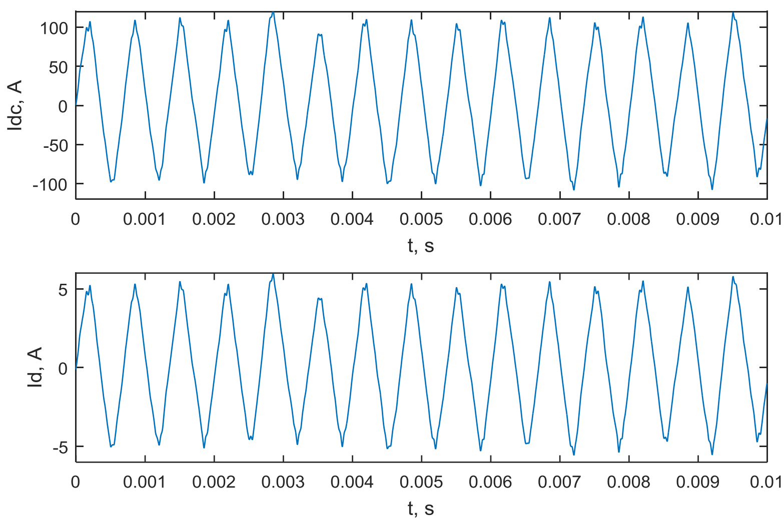

Figure 8. Scaled time segment of figure 7

A self-diagnosis method was proposed to increase the shift of the Fm criterion caused by failure of any supercapacitor. The main idea of self-diagnosis method is to generate a high-frequency periodic current I_{DC} with magnitude in order of the nominal charge / discharge current of the supercapacitor storage. So the control system periodically gives such an impacts on ES for the short time of an order of couple of hundreds of milliseconds. Figures 7 and 8 shows energy storage current I_{DC}, unbalance current Id and normalized measure of unbalance current Fm under self-diagnosis mode.

The use of the self-diagnosis mode provides an increase in the change in the Fm criterion from 0.009 to 0.320.

VI. CONCLUSION

Both normal and abnormal modes of operation of a high-voltage supercapacitor battery energy storage are modeled. It is shown that the known method for protecting an AC capacitor bank can be adapted to a supercapacitor battery under constant voltage in a buffer mode. A self-diagnosis method is proposed, which allows to increase the sensitivity of protection by passing a short-term high-frequency current through the battery.

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