Simplified control system for grid-tied modular multilevel based energy storage

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ABSTRACT

Microgrids and networks with renewable energy sources are increasingly common. A network energy storage device is required for their normal operation. Common high-voltage storage devices have many disadvantages. It may create a risk of fire or electric shock if it is not handled carefully. It is not possible to utilize used batteries both safely and effectively at the same time. Using a small number of levels negatively effects on output voltage curve quality. Large assemblies already may be divided into smaller ones to be serviced and replaced independently. The article proposes an approach to development for an energy storage system not with a concentrated, but with a distributed battery where small battery assemblies are placed in the separate cell DC-link of a modular multilevel converter. A solution is also proposed that ensures the sensors minimization to ensure the possibility of accumulation and return of energy to the network.

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1. INTRODUCTION

Modern power grids include alternative power sources. A lot of works focused on working point optimization for alternative power source for example [1], [2]. There are many tools [3]–[5] and instruments [6]–[8] to coordinate alternative source and power grid. To acquire power balance grid-tied energy storage is needed. However, the classical energy storage circuit has a number of disadvantages:

- The efficiency decreased at low load, due switching losses predominate which are weakly dependent on the load, in contrast to the modular multilevel converter (MMC)
- The DC link utilization factor, is lower than in the MMC, even in multilevel classical inverters, since the MMC has an incomparably greater levels number [9]
- Used batteries is incompatible for the classical circuit, as they require additional complex device for balancing and protecting batteries
- It is more difficult to divide a single storage into sections for easier transportation and installation
- High-voltage battery leads to dangerous installation. A part of the work has to be done under high voltage
- Classic energy storage modernization is difficult as monolithic storage is very sensitive to the cell heterogeneity

For these reasons, a new generation of storage devices based on the modular converter structure, described in Dekka *et al*. [10] is beginning to develop and be introduced.

Development of modular multi-level storage devices appeared after alternative energy sources spreading. Examples of such developments for electric transport are given, for example [11] and [12]. Both of these publications propose the design of a three-phase energy storage device with a delta connection of the phases and a complicated module structure which makes possible parallel connection of the modules at low voltages. This is relevant for a car drive, but for a drive in an AC network with constant parameters (the amplitude of the first harmonic and its frequency), such complications are redundant, although the calculations of efficiency and economic efficiency given in Yang *et al*. [12] show that MMC with battery energy storage with such a complication of the structure are more efficient than classic ones. In Forstl *et al*. [13], a simpler module structure is proposed, with less structural redundancy due to a decrease in the number of active keys and, therefore, it is less reliable.

2. COMPLICATION PROBLEM OF MODULAR MULTILEVEL SCHEME

The first control problem is the regulation of the residual charge of the batteries in individual modules, given, for example [14]–[16]. The problem of the given examples was solved by installation of individual sensor on each module. This is acceptable in the case of a small number of modules, However, in the case of a large number of modules, reaching hundreds, the installation of such a number of galvanically isolated voltage meters leads to a noticeable increase in the cost of the device.

The rejection of such a huge sensor system will simplify the development of the hardware component of the proposed device and reduce the cost of manufacturing. Balancing the charge is not the only problem. Since a MMC with a rechargeable energy storage is positioned as highly efficient and it is, a lot of work is devoted to calculating and comparing its efficiency with different voltage generation algorithms, for example [17] and in comparison, with classical structures of two and three-level converters, for example [18]. Yang *et al*. [19] describes the capabilities of the considered storage device for the task of blocking short-circuit currents. Reite [20] describes the possibility of forming a distributed storage device based on a modular structure is described. Such works illustrate the necessity and relevance of further development of modular multi-level storages.

The MMC makes possible simplifying of the design of a grid-tied UPS and increase its efficiency, but it has a very high complexity of control. For correct operation, it is necessary to have information about the voltage of each module and the arms, the currents in the arms, the load and DC voltage for correct operation. In the scheme of a MMC, which is a prototype of the scheme under consideration, when using capacitors to store energy in the module, the task of measuring voltage could only be solved by equipping each module with a voltage sensor, which significantly increases the complexity of control and the cost of the device.

Batteries have a much larger capacity than capacitors, [21] and therefore allow the use of approaches to measuring and balancing the voltage of time-separated modules, which reduce the number of voltage sensors. To increase efficiency and reduce the number of energy conversion stages transformerless UPS are used instead of transformer UPS [22] in high-power installations. The obvious disadvantage of a transformerless UPS is the high du/dt value. To compensate for this disadvantage, a transformerless UPS has to be fitted with a filter that smooths out current and voltage ripples, but has mass, dimensions, additional losses and time delay. As it was presented in [23] and [24], the dynamics of the filter negatively affects the speed and quality of transients when synchronizing the converter with the network.

Also, when using a high-voltage battery a separate cell voltage balancing device is necessary to protect them from deep discharge and overcharging that negatively affect the health of the battery [25]. The MMC allows to scale the operating voltage and has low energy losses during operation [26]. However, the modular circuit is difficult to control and requires a large number of sensors, which is illustrated in Figure 1.

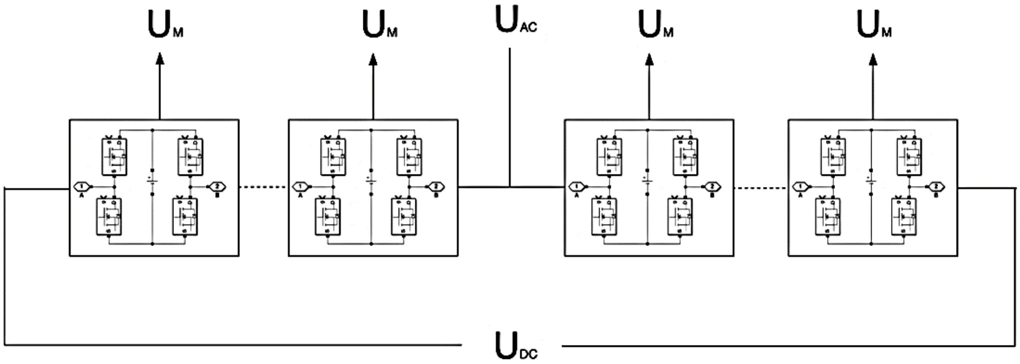


Figure 1. The measurements required for the operation of the modular converter

Figure 2 shows a general list of tasks needed to be solved when managing any MMC, also those contained in the UPS. Figure 2 shows the classical converter does not have even a half of the tasks that are necessary to control the MMC. The classical approach to the implementation of MMC is a hierarchical control and measurement system. The division of the management system into levels and the correct distribution of tasks between them allows to reduce the number of information flows and the complexity of their processing. However, the hierarchical approach too costly in the field of low and medium capacities, where the competition of MMC consists of classic two- and three-level converters with a huge number of ready to use solutions. The largest number of sensors in MMC control is required to measure the voltage of individual modules. Reducing the number of such sensors is most effective way to simplify the MMC control system.

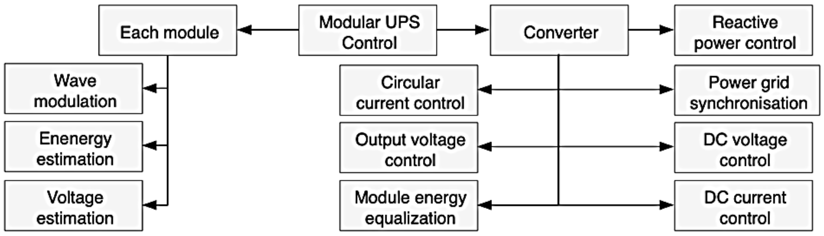


Figure 2. Hierarchy of the MMC based UPS management system

3. PROPOSED CEIL VOLTAGE MEASUREMENT

The voltage of the modules can be determined in three different ways: direct measurement, indirect measurement and evaluation with the help of a state observer. Direct measurement is the simplest and most accurate. It does not contain additional measurement errors and does not require information about the state of the system and its properties. However, each module requires its own galvanically isolated voltage sensor. There are ready-made integrated solutions with digital interfaces that can be galvanically isolated via optocouplers and there are more expensive solutions based on the Hall effect used in medium and high-power converters.

3.1. Method description and assumptions

Indirect measurements do not require the implementation of complex large number of sensors and processed information signals in the MMC. The cost and complexity of implementing such a measurement system makes modular circuits more competitive against the classical solutions for small and medium-sized capacities. Several ways of indirect measurement are possible depending on the assumptions made.

Using stepping modulation only one module is switched at one time, both calculating the measurement error and calculating the voltage of an individual module in a group is significantly simplified. The result will always be a triangular matrix. The voltage of each module will be defined as:

$$U_k = |u_{i-1} - u_i|$$

where $i -$ the number of the current voltage stage, $u -$ the voltage of the module group at the i-th switching step, $U_k -$ the voltage of the cascade switched on at the i-th step. The assumption with a limitation of the voltage regulation rate is the best way to measure as long as the frequency of the first harmonic of the generated voltage is significantly lower than the performance of the voltage meter and significantly higher than the rate of voltage changes of the modules. The sensor measures voltage of the first connected module, the first two, etc. until the entire group is measured or the voltage limiter is triggered and the device is disconnected. The battery condition is estimated in two stages.

The first stage is voltage monitoring. Protection against deep discharge or overcharging is carried out at the same time. Also, if it is implemented programmatically the storage capacity of each module is adjusted according to the cut-offs of energy given or received between the states of charge and discharge. To reduce the number of sensors the measurement is carried out in groups of eight cascades on the AC side. The choice of the number of simultaneously measured cascades is caused by an accommodation between the measurement error of the voltage sensor, the complexity of processing and the range of changes in battery voltage between the maximum and minimum charge.

3.2. Modules state of charge estimation

The second stage is the evaluation of the energy given or received by the battery. The mathematical description of the battery voltage differs from the description of the capacitor. Moreover, the change in battery voltage is not so significant over time. The most informative indicator for storage battery are the accumulated charge (state of charge, SOC) and the residual charge (state of discharge, SOD), expressed as a percentage and related by the expression SOC = 100–SOD.

The main electrochemical storage device in modern electronics is a $LiFePO_4$ battery. The simplest battery model is the internal resistance model based on Thevenin's theorem and the voltage on the battery plates in this case can be determined as:

$$U_{batt} = U_{int}(SOC) - R_{int} \cdot I_{bat} \, , SOC = SOC_0 - \frac{\eta}{C_E}\int I_{batt} dt \, , U_{int} = f(SOC)$$

where U_{int} − the internal voltage of the battery due to chemical processes occurring in it, V; SOC − the residual battery charge, %; η − the battery efficiency; C_E − the battery capacity, Ah; U_{batt} − the voltage on the battery plates, V.

There is other [27], more accurate models of the second and third order, also constructed on the basis of Thevenin's theorem. The dependence of the voltage on the residual charge is nonlinear and can be approximated by a polynomial [28]. However, there are proposals for approximating this curve with an exponential function [29], which will not be considered in the paper due to greater computational complexity. The current flowing through each module will be only the phase current, since the introduced simplification of the storage circuit does not require circulating currents. Assuming that the measurement frequency is significantly higher than the frequency of the signal change, the battery voltage in the module can be restored according to the battery model [30]. The estimated value must should be compared with the measured value and adjusted to track the state of the battery and predict the need for its replacement and charge:

$$U_{batt} = U_{int}(SOC) - R_{int} \cdot I_{phase}, \;\; SOC_i = k_i \cdot \int S_i(t) \cdot i(t) dt$$

where C_i − the given (received) battery charge of the i-th cascade; $i(t)$ − the phase current; $S_i(t)$ − the state of the cascade during operation. It can be equal to "0" if the cascade is shunted, "1" if the cascade is switched to the state taken as positive and "-1", if an inverse voltage is formed; k_i − a scale factor that allows considering the spread of battery parameters in different modules. To form a grid voltage with an amplitude of 310 V, 100 to 120 series-connected lithium cells will be required. Grouping four cells in series, which is a common and safe solution, with this approach to measurements, three to four voltage meters per phase will be required.

4. MODELLING OF MMUPS WITH PROPOSED INDIRECT MEASUREMENT

The voltage change on the battery modules is necessary to be controlled. Dynamic characteristics of battery cells is much slower than in capacitors. The battery voltage data can be used to correct information about the remaining charge and to protect the cell from deep discharge and overcharging. If an electrochemical storage device is placed into the module, the module can act as the main source of energy. This is illustrated in Figure 3(a). To reduce number of modules it is necessary to use reverse polarity schemes. The model of a separate group of modules with part responsible for sorting and choosing the sequence of switching on modules by SOC is shown in Figure 3(b). Function block listing placed in Listing 1.

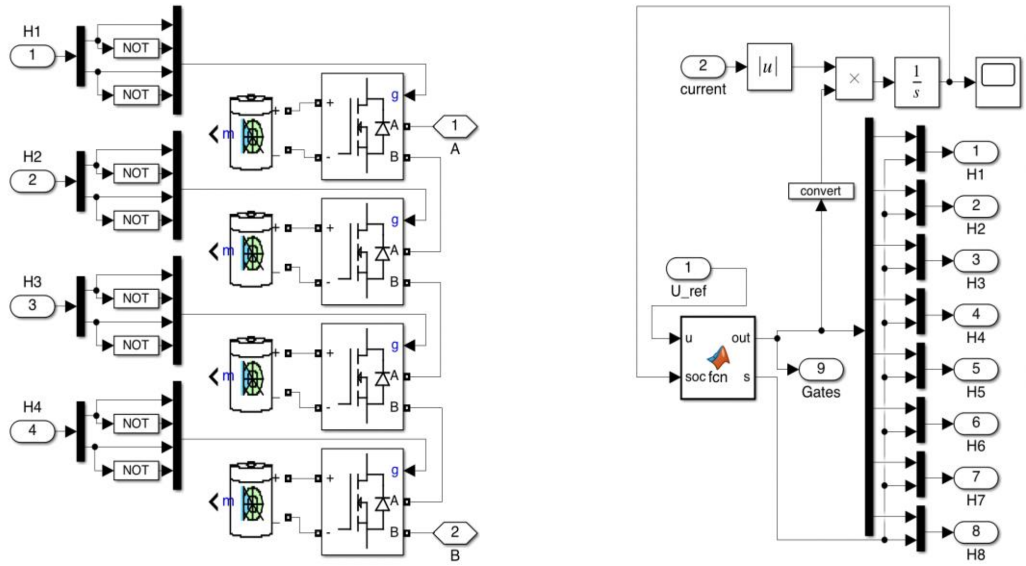
Figure 4 shows upper level of model (a) and PR-regulator (b) which was chosen to simplify the control system [31]. Proposed measurement method realization showed on Figure 5 and listing. Figure 5 show solving for triangle algebraic equation system of eight variables. The simulation results are shown in Figure 6 in the form of output voltage and curves of SOD in one of the groups of modules. Function listing for indirect voltage estimation is placed in Listing 2. Figure 7 shows voltage estimation compared to modules voltages.

Listing 1 – Switching function with SOD equalization

```
function [out, s] = fcn(u,soc)
N=8;                %module number
s=u>0;              %polarity check
y=floor(abs(u));    %rounding voltage
if y>N              %prevent exceeding error
   y=N; end
I=zeros(N,1);       %index vector
[B,I]=sort(soc);    %sort modules by SOC
for i=1:y           %activate i modules
   tmp(I(i))=1; end
out=xor(tmp,s);     %evaluate polarity
```

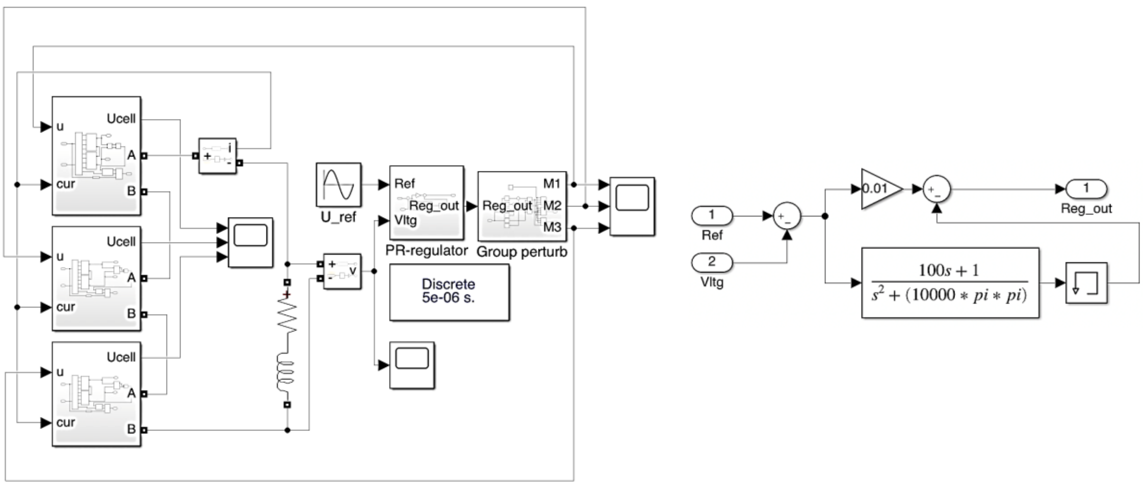
Listing 2 – Indirect voltage estimation

```
function [Out, Mo]  = fcn (U, G, Mi)
Mo=Mi; Out=zeros(8,1);   %variable initialization
for i=1:7
   if sum(G)==i
      Mo(i)=U;               %save voltage values
   end           end
if sum(G)==0
   Mo(8)=U;                  %save last voltage value
end
Out(1)=Mo(7);
Out(8)=Mo(8)-Mo(1);      %calculate modules voltage
for i=2:7
   Out(i)=-Mo(i)+Mo(i-1);            End
```



(a) (b)

Figure 3. Close up view (a) group of four modules and (b) energy balancing system for two groups of four modules



(a) (b)

Figure 4. Close up view (a) a whole model of single-phase storage with control system, and (b) PR-regulator in voltage control loop

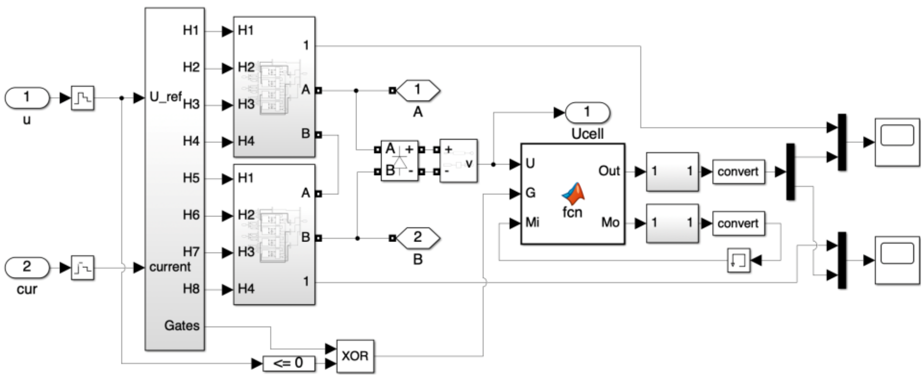


Figure 5. Voltage fixation at each switching and basic managed group of modules and single-phase multi-level UPS model

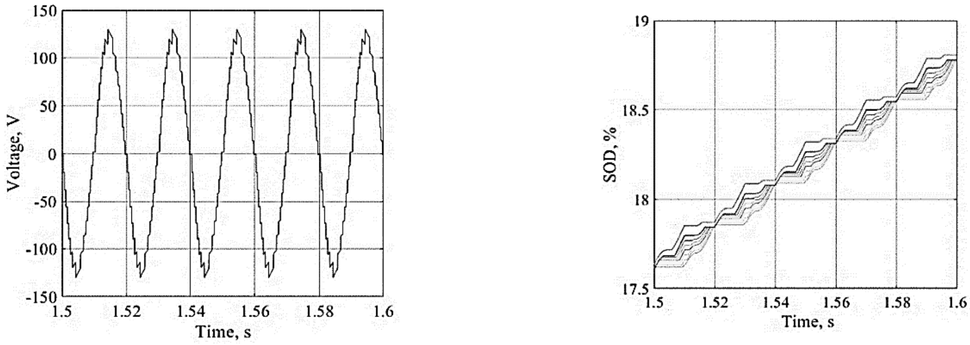


Figure 6. Output voltage curve and battery charge consumption within one group of modules

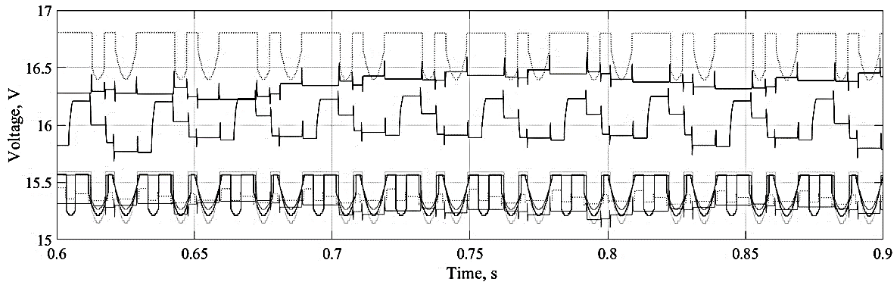


Figure 7. Module voltages measured (gray) and estimated (black)

5. RESULT AND DISCUSSION

Figure 6 show voltage curve with low THD, which produced by presented UPS scheme and SOD of each module. As we can see balancing part of algorithm from listing 1 works correctly and SOD rises equally between modules. From Figure 7 we can see that voltage estimation also works, but voltage drop on transistors must be taken into account. And transitions due commutation creates significant disturbance.

Using of indirect measurements has its own difficulties. Any measuring device has a measurement error. This error increases using indirect measurement. If the sensor's operating range is comparable to the measured parameter, the measurement error does not act in engineering tasks and usually is not considered.

For example, measuring the voltage of ten modules with one sensor the voltage of one module will be no more than 10% of the measurement range, and the change in this voltage during charge and discharge in the case of common $LiFePO_4$ cells will be only 3% of the measurement range. With a relative error of only 1% deep discharge or overcharging of the battery are practically guaranteed, otherwise it is need to use a bit more than half of the capacity of the battery to protect it from damage or fire. But it is impermissible to infinitely increase the size of the processed group of modules to maintain sufficient measurement accuracy.

In this paper the choice is made on eight modules using one common sensor. This solution already allows to expand the capacity range used up to 70%, which is acceptable for a layout and whole for the battery. The transition to a modular UPS scheme allows using a MOSFET as an element base with an increase in efficiency, which is shown in [32]. The main difference, in losses in the power key, is the approach to assessing losses. The main losses of MOSFET are ohmic, and IGBT losses are commutation. In MOSFET, active losses are proportional to the square of the current, and in IGBT – to the saturation voltage of the junction and the current flowing through this junction.

To reduce the number of elements, it is necessary to implement several solutions; i) Using module schemes with a reduced number of elements; ii) Rejection of direct measurement of module voltage; and iv) The use of non-resource-intensive modulation algorithms to reduce the load on the applied microcontroller and digital interfaces. Various module schemes for multi-level modular converters are considered in detail in [33].

6. CONCLUSION

The comparison of direct and indirect measurements on shows that the proposed method for indirect voltage measurement is working on small loads correctly and make large deviation on high current conditions, when voltage drop on switches became visible. So, it is necessary to took into account voltage drop on battery cells and switches. Unfortunately, simplest approach with only indirect measurement can be used only in purpose of cell protection, where measurement error can be compensated by simple margin. As result for proposed indirect measurement method; i) To provide accuracy of voltage measurement it is necessary to add voltage drop on battery cells internal resistance and voltage drop on active switches; and ii) Indirect measurements can be used in limited condition of small current, for example. The simplest solutions unfortunately have disadvantage, but it still helps to reduce the cost of the converter.

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