Overview of "Power Electronics for Grid Connection of Utility-Scale Battery Energy Storage Systems"

Abstract – The IEEE article, "A Review of Power Electronics for Grid Connection of Utility-Scale Battery Energy Storage Systems" by Guishi Wang, et al. published in July of 2016 takes an in depth look at the application of power electronics in utility scale battery energy storage systems for use in renewable energy systems. Renewable energy systems are typically unable to generate a constant amount of power for indefinite time due to dynamic environmental factors. Through the use of battery energy storage systems, we are able to compensate for these ever changing environmental factors. Battery energy storage cannot exist on its own. Several power electronic topologies are employed in battery energy storage systems, which allow for energy to be safely and dynamically stored for use in commercial scale renewable energy production and usage. The paper presents a review of these power electronic topologies that have been proposed in either industry or academic literature for use in battery energy storage systems. It continues into a comparison of the better power electronic topologies currently being used on the market in terms of cost and efficiency.

Renewable Energy Sources have long been thought of as a possible source of power for the places in which humankind work, play, and lives. The concept of powering our society from multiple energy sources is a relatively new but increasingly important focus area of power systems engineering. The engineering of power systems utilizing Renewable Energy Sources is going to be vital for both industrialized and emerging countries in the coming decades, largely due to Renewable Energy Sources being readily available in many parts of the world where there are limited resources to meet the power demands of human civilization. Now that modern technologies have increased human civilization's dependency and demand for readily available electricity, it is imperative to utilize Renewable Energy Sources as part of a power grid that utilizes multiple sources of power together to ease the burden of energy demand on one resource. Due to the intermittent nature of renewables, utility scale battery storage systems are growing as a solution to storing large quantities of renewable generated energy for future use. Utility-scale battery energy storage systems (BESS) enable renewable energy sources to be a viable alternative to non-renewable peak demand gas turbines. Depending on the renewable energy system generating power, renewables can generate either alternating current (AC), such as in the case of wind or tidal turbines, or direct current (DC) such as in the case of solar. Since batteries store DC only and the utility grid utilizes AC, power conversion must take place to employ this technology. The only way to achieve power conversion and stability of the system is through the use of power electronics. There are several types of presently known power electronic topologies used to achieve this power conversion, but since this is an emerging technology with a great deal of research still needing to be done, the best topology or all the possible topologies might not yet have been discovered. The presently known topologies will be presented in this paper, as well as an analysis of five specific topologies.

There are two categories of BESS topologies that exist: Transformer based and transformer-less based. A block diagram of the two systems operations are shown in figure 1. The transformer based topology is the most conventional method, which utilizes an output step up transformer with 2 level (2L) three-phase converters (one Insulated Gate Bi-polar Transistor - IGBT pair per phase), as shown in figure 2. The transformer on the output of these converters steps up the voltage from low voltage battery range (<600V) to medium voltage utility grid distribution range (2.4kV+). Complex multi-level converters can also be used to fine tune harmonic performance such as a three level converter.

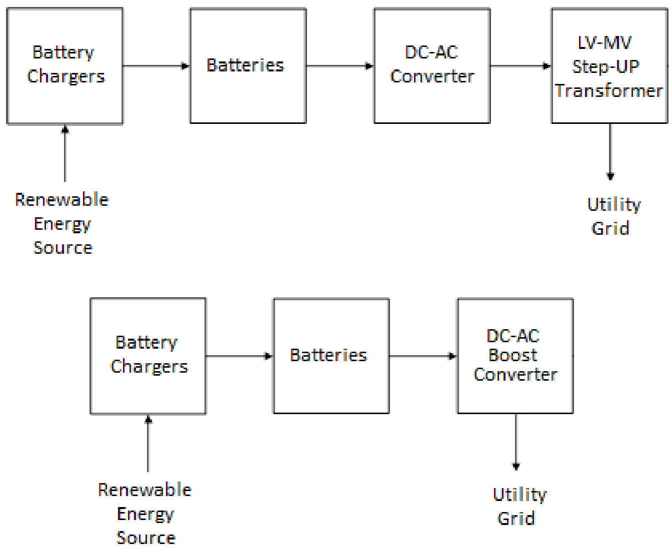

Fig. 1. Functional Block Diagram of Transformer Based BESS Topology (top)
Functional Block Diagram of Transformer-less Based BESS Topology (bottom)

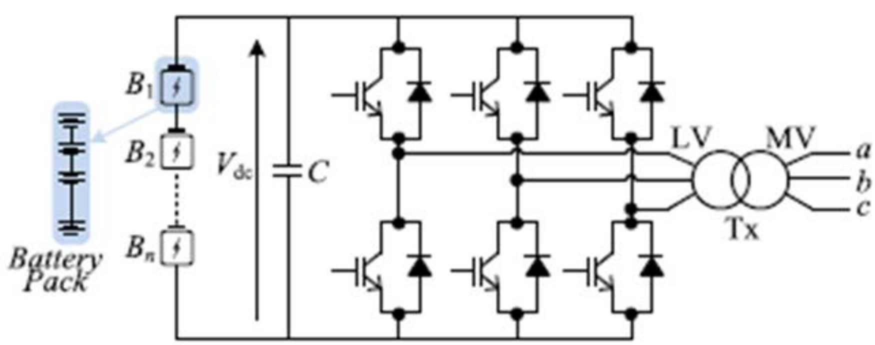

Fig. 2. Conventional PE unit using a 2L converter and transformer.

The second category of BESS topology is one which does not utilize a transformer. Instead, it contains series connected semiconductors which allows for direct connection of the converters to the medium voltage utility grid without the use if the step up transformer previously discussed. In this topology, enough IGBTs are connected in series to block the DC-link voltage. The DC-link is the connection between the DC batteries (regulated or unregulated outputs) and the DC-AC system. Another topology similar in concept utilizes series connected sub-modules. Two examples of this topology are the Cascaded H-Bridge Converter (CHB) and the Modular Multilevel Converter (MMC). The CHB contains cells comprised of three phase legs and semiconductor H-bridges connected in series with one another. The cascaded nature of the H-bridges allows for incremental boosting from low voltage battery range to the medium voltage grid range. This topology requires advanced industrial controls to eliminate charge unbalance between the batteries of each cell in the converter. The modular multilevel converter (MMC) can have one of two configurations. One configuration contains a long string of series connected batteries which make up a centralized battery bank with series connected sub modules. The long battery strings cause a number of problems within the system. One way to alleviate the various problems associated with large battery strings is to have batteries distributed into each sub-module. The other configuration contains one battery distributed to each series connected sub-module. A comparison of both types can be seen figure 3. In MMCs, circulating current between batteries helps charge unbalance issues, but increases switching losses due to conduction. Along with this, there is a need for large sub-module capacitors to filter large fundamental harmonics.

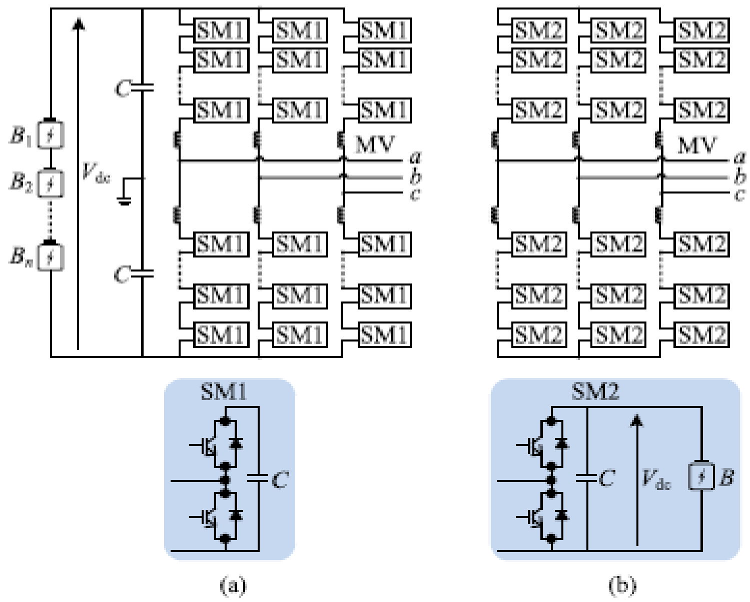

Fig. 3 MMC and corresponding SMs: (a) centralized batteries on the dc-link; (b) distributed batteries in the SMs.

The controllable common DC-link uses DC to DC converters between battery strings and the ac converters as the DC-link. This eliminates charge imbalance by regulating the varying dc from each battery string output and filters low order harmonics from entering the batteries which increases the battery life. Simple boost converters as shown in figure 7a, are used to increase voltage closer to medium level grid level. System requirements specifications are still under development for BESS, and it is not known at this time whether or not isolation will be deemed as a requirement of BESS. Isolation may become required due to overcurrent and operating temperature concerns between the medium voltage grid and battery system. The use of a dual action bridge or DAB converter employs a high frequency switching scheme through a transformer and achieves galvanic isolation, as shown in figure 4.

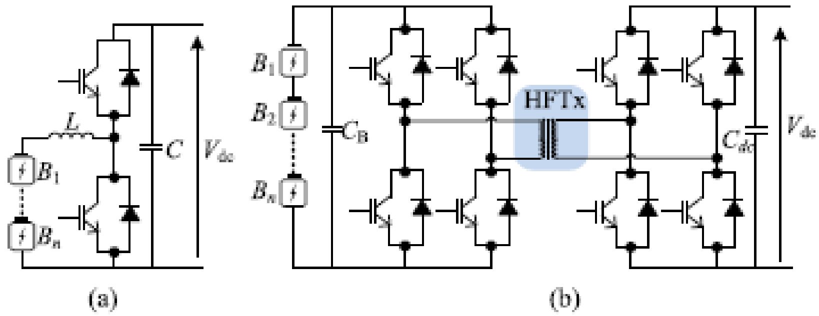

Fig. 4 Common dc-dc converter topologies to control the power flow between the common dc-link and batteries, (a) boost converter, and (b) DAB converter.

The final type of topology that is presented is the Hybrid Energy Storage System (HESS). HESS combines the advantages of two topologies in one system. In order to utilize the advantages of a HESS, the individual topology components must be interfaced together with controls. There are three main configurations that are presented for HESS: uncontrolled, semi-controlled, and fully-controlled as shown in figure 5. In uncontrolled HESS, power from the batteries is not regulated. Impedance is needed to limit voltage imbalance surge current from parallel battery strings, such as during a fault condition. Semi-controlled HESSs contain DC to DC converters on half of the battery strings. There is no need for current limiting impedance between the strings of this topology. Voltage of half of the system is regulated to match the other half. Still, some variation can still exist in voltage in the unregulated half. The fully –controlled HESS contains a DC-DC converter on each of the battery strings. This allows for a common DC-link and battery output voltage regulation. AC output is then regulated by complex control algorithms.

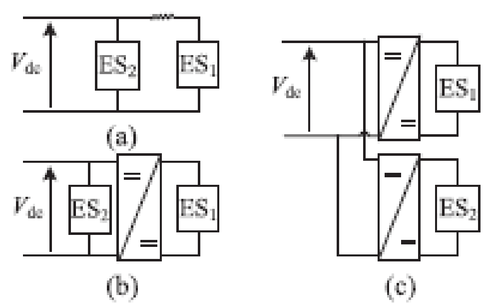

Fig. 5 Typical categories of configurations to connect multiple ES resources: (a) direct connected; (b) half controlled; and (c) fully controlled.

The experiment presented in this paper compares five utility scale BESS topologies all needing to produce 30MVA of three phase power at a nominal grid voltage of 22kV. The benchmark system of the experiment was a 2L converter utilizing a traditional line-frequency (60Hz) step-up transformer. Four other topologies (all without a transformer): 2-level converter, 3-level converter, Cascaded H-bridge (CHB), and Modular Multilevel Converter (MMC) with specifications needed to achieve 30MVA of three phase power at a nominal grid voltage of 22kV are presented in table 1 with the benchmark system (the system to which all other system performances are being compared). The systems performance parameters measured are efficiency, power losses under two various load conditions, and cost.

TABLE 1
SPECIFICATIONS OF SELECTED PE UNIT CONFIGURATIONS

Configuration	2L+Tx	2L	3L	CHB	MMC
Three-phase Power	30 MVA				
Nominal Grid Voltage	22 kV				
# of Converters	15	1	1	1	1
# of cells / SMs	–	–	–	10	40
Transformer turn-ratio	22/1.2	–	–	–	–
V_{acpeak}	1.15 kV	18 kV			
# IGBT in series	1	18	9	1	1
V_{dc}, kV	2.3	36	36	2.3	36
Rated IGBT Voltage	3.3 kV				
IGBT cosmic-ray failure rate [81], [82]	0.7				
Continuous dc collector current	1 kA				
Rated RMS Current	825 A	788 A			
Safety Factor	1.3	1.4	1.4	1.5	1.5

In a comparison of efficiency, the simple 2L converters (with & without transformer) are the most inferior topologies with respect to efficiency with the efficiency dropping up to 6% with increased switching frequency. The best efficiency performance came from MMC & CHB topologies where the effects of higher switching frequencies were found not have an adverse effect on efficiency. This is illustrated in figures 6, where a power level of 0.8 pu was used to compare the topologies various equivalent switching frequencies. Figure 7 goes on to compare the various topologies at various power levels.

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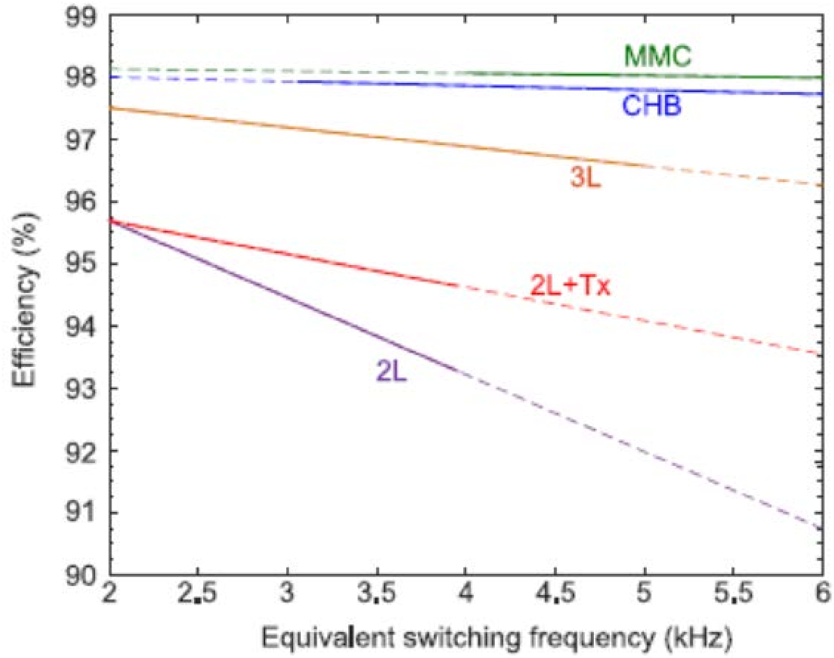

Fig 6 Efficiency of compared configurations at various equivalent switching frequencies with the power level of 0.8 pu.

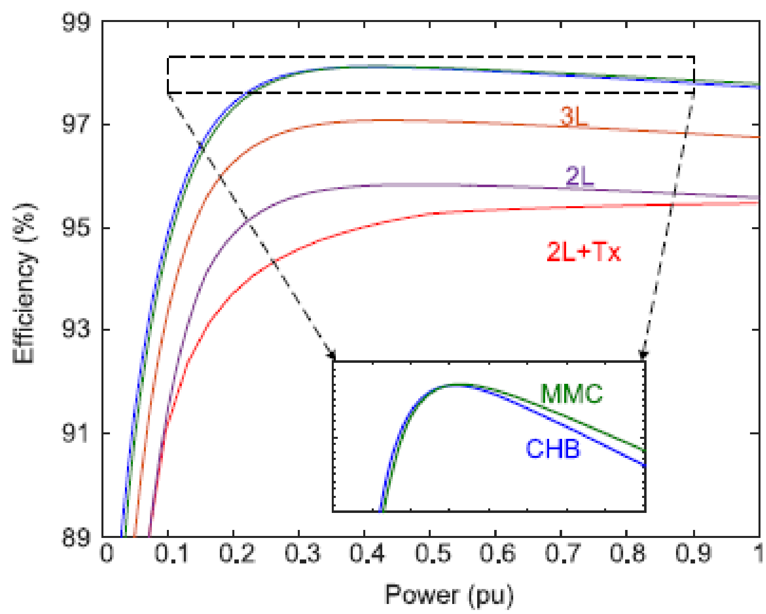

Fig 7 Efficiency of compared configurations at various power levels.

Power losses for the various main components that comprise each topology at two different load levels, under light load (10% loaded) and heavy load (80% loaded) are analyzed.

Results at 10% load, as shown in figure 8, yielded the largest power losses from DC-DC conversion. The smallest power losses at 10% load came from switching losses, which were almost negligible in all systems. At 80% load, all switching losses increase, but switching losses become significantly larger than under light load, as shown in figure 9.

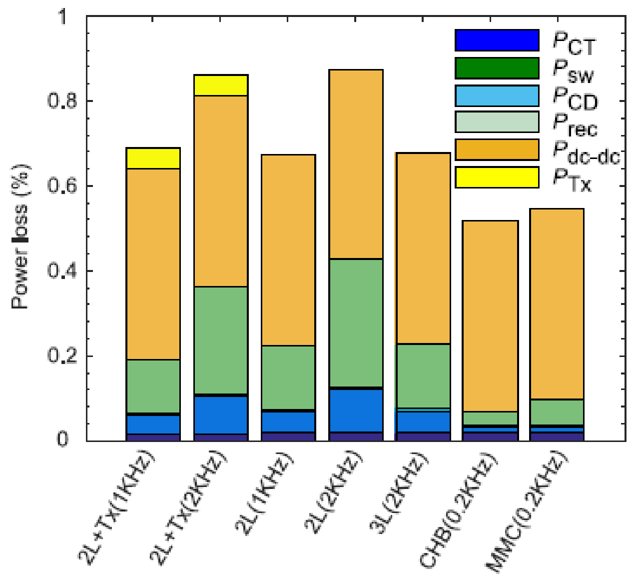

Fig. 8 Breakdown of entire PE unit losses for different configurations at 10% load.

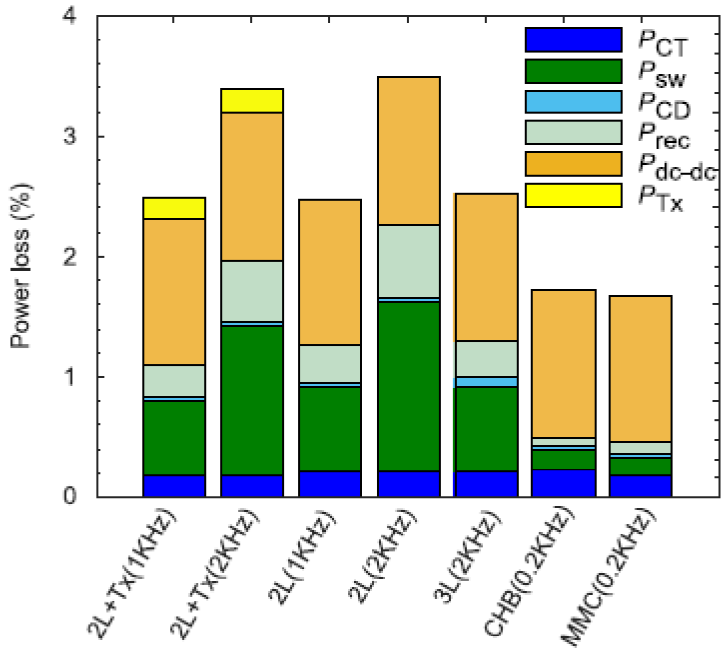

Fig. 9 Breakdown of entire PE unit losses for different configurations at 80% load.

In the cost analysis, the costs of several main basic system components are considered only – Capacitor (DC-link cap), Silicon (Switching devices), Filter (on rectified output), and Transformer (applied only to benchmark topology – 2L+Tx). The most cost effective typology (in terms of the components analyzed) is the CHB as compared to the benchmark (2L+Transformer) topology at ~20% less. The desire to eliminate a step up transformer arises in the fact that the transformer accounts for ~40% of the benchmark system cost seen in figures 10 and 11.

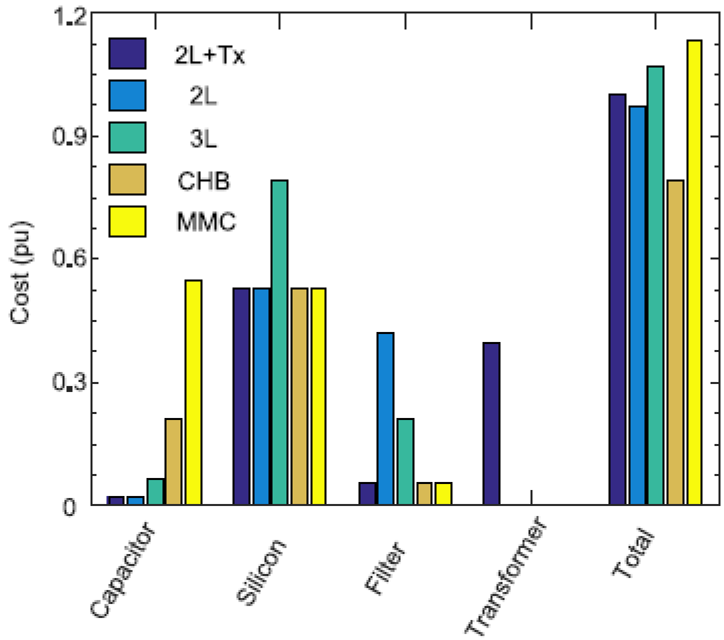

Fig. 10. Cost Breakdown per Component for Each Topology Per Unit Cost

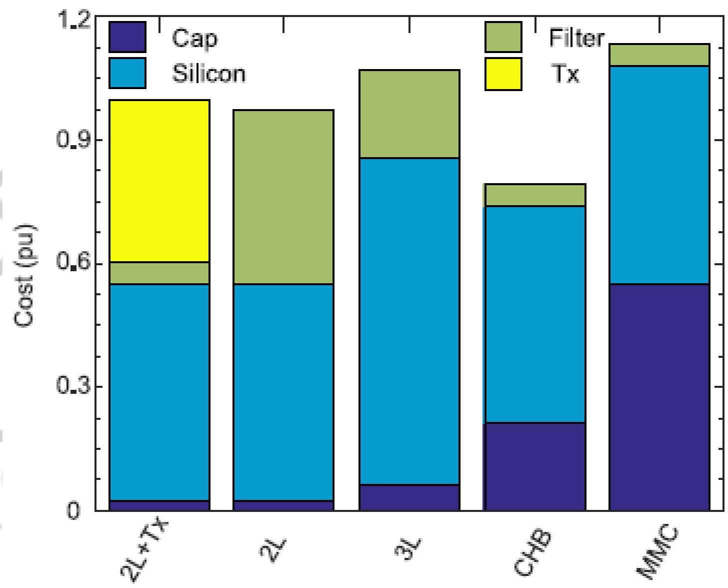

Fig. 11. Cost Breakdown per Topology for Each Component Per Unit Cost

There are a variety of specific issues that can be associated with battery energy storage systems. Typically batteries are sensitive to overcharge without DC-DC regulation. Aside from this, battery life and safety issues arise from low order harmonics from grid faults. Another consideration is that heat distribution must be considered when stacking batteries. If batteries are stacked without adequate cooling, performance and battery life may be affected. Two specific topologies: CHB and MMC have limitations during sustained grid imbalance from unequal charge/discharge of batteries in each phase leg. Less filtering in the various topologies reduces the presence of unwanted resonances in the grid.

As a result from analyzing this data, transformers-less configurations have been found to have lower power losses than those with a transformer, but are more complex with more power electronic devices. CHB has the lowest system cost (not including additional DC-DC converters). DC-DC converters were found to account for a large portion of losses in all topologies. As of present day, industry standards & requirements are not currently fully developed for BESS. This makes it difficult to accurately compare the all topologies with all systems components and characteristics considered. More research in the coming years must be done to further analyze various system costs, in order to determine the best topology for various system parameters and desired functions.

Works Cited

Guishi Wang, Georgios Konstantinou, Christopher D. Townsend, Josep Pou, Sergio Vazquez, Georgios D. Demetriades, Vassilios Georgios Agelidis. "A Review of Power Electronics for Grid Connection of Utility-Scale Battery Energy Storage Systems." *IEEE Transactions on Sustainable Energy*, vol. 7, no. 4, October 2016. Web. 6 Dec. 2016. < http://ieeexplore.ieee.org.libdb.njit.edu:8888/stamp/stamp.jsp?arnumber=7506096>.