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Comparison of Military Handbook and the FIDES Methodology for Failure Rate Estimation of Modular Multilevel Converters

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***Abstract*—Power electronics converters are crucial for power generation, transmission, and distribution. The modular multilevel converter (MMC) is highly valued for its ability to handle high power levels, versatility in reconfiguration, high efficiency through small-capacity submodules (SMs), and robust control capabilities. A failure of a power electronics converter could result in disruptions in the flow of electrical power, which could have severe consequences for people and equipment relying on it. Thus, the reliability of power electronics converters is critical to maintaining the reliability of the electrical power system. Two well-known methodologies, the military handbook (MIL) and the more recent FIDES, can be used to evaluate the MMC's reliability. Both methods consider various factors to estimate the component's failure rate, resulting in different reliability parameters. In this paper, the reliability of the MMC is estimated using both methods, and the results are compared for standby and active redundancy strategies. Lastly, a generalized cost form that considers operational cost, capital cost, redundancy strategies, reliability methods (MIL and FIDES), and the MMC's annual average loading is presented.**

***Index Terms*—MIL handbook, FIDES, MMC, reliability, redundancy, failure rate, cost.**

I. Introduction

The Modular Multilevel Converter (MMC) is a cutting-edge power conversion technology that has gained widespread recognition across various applications, such as wind power plants, direct high-voltage direct current (HVDC) transmission systems, and sustainable energy sources [1]. MMCs offer several advantages over conventional power converters, including improved energy efficiency, reduced harmonic content, and increased power density [2].

The estimation of the failure rate of components within the MMC system is a crucial aspect of designing a reliable system [3]. In literature, two methods have been widely used to estimate the failure rate of components: the FIDES [4] and the Military Handbook (MIL) [5]. FIDES is a more recent method that utilizes statistical analysis to estimate the failure rate of components within the system. On the other hand, the MIL handbook established in 1994 employs a set of assumptions and guidelines to estimate the failure rate of components [6]. In [7], a method is proposed for the optimal selection of power electronic switches for MMC based on reliability and lifetime requirements. It demonstrates the suitability of the most economical switches.

Numerous studies have been conducted in recent years to evaluate the system's reliability at the component level [8], [9], converter level [1], [10]–[15] and power system level [3], [16]–[18]. These studies provide valuable insights into the design and optimization of the system. For instance, in [1], the authors applied the mission profile and estimated the MMC reliability with different switch ratings. Different converter configurations were compared in [10], and a method was proposed to select the optimal converter for various power ratings. In [11], various redundancy schemes' effect on the MMC's dynamic behavior and efficiency was evaluated. In [19], the fault-tolerant MMC was assessed. In [14], the impact of two redundancy strategies was evaluated, and a cost-based method was proposed to select the optimal redundancy strategy. The authors of [12] evaluated the impact of redundancy in MMCs with various switch-blocking voltages. In [13], the ways of applying redundancy, modularity, and reconfigurability to improve the system's reliability were generalized. In [15], the authors emphasized the need for a criterion to select which components should be considered in the reliability analysis.

The FIDES method, an approach for estimating the component failure rate, has received limited attention in the literature. A thorough review of the existing studies on FIDES reveals that authors have employed it in [6], [20]–[23] to evaluate the reliability of various power electronic systems. In [20], FIDES is compared with other established reliability methods such as MIL and PRISM. Additionally, [6] compares the failure rate estimation of power electronics switches using both FIDES and MIL, concluding that FIDES produces lower failure rate estimates than MIL. Likewise, authors in [21] and [22] apply FIDES to estimate the reliability of DC-DC converters, and [23] employs FIDES to evaluate the reliability of a single-phase double-stage PV inverter.

This study focuses on evaluating the reliability of MMCs at the converter level, utilizing two different reliability methodologies. The impact of implementing redundancy is also analyzed to highlight the significance of the chosen reliability methodology. In addition, the cost of MMCs in terms of the initial investment and operational losses is quantified. The remaining part of the document is structured in the following way. The section II describes the attributes of the system and the approach used to evaluate the MMC reliability. The section III explains redundancy. A specific example is presented in section IV, and the system's cost, reliability, and operating costs are evaluated. Finally, the paper is summarized in section V.

II. System Characteristics and Reliability Scheme

A. System Description

The layout of a half-bridge SM in a three-phase MMC is shown in Fig. 1.

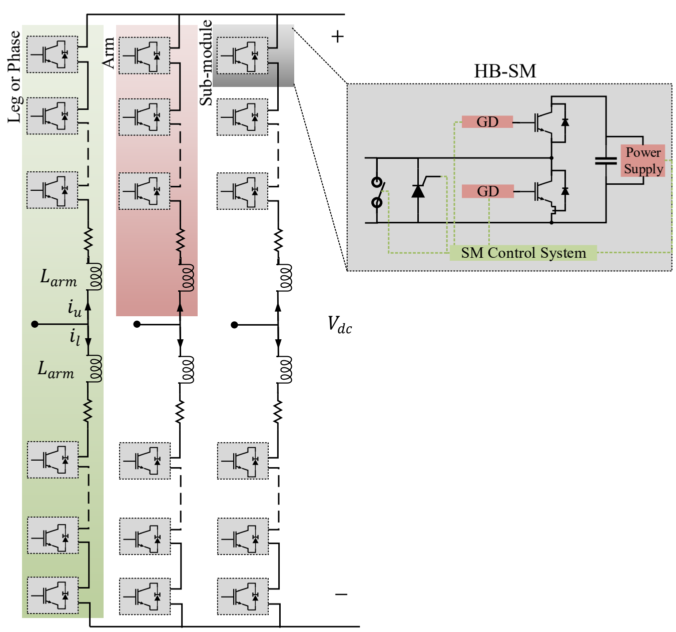

Fig. 1. MMC configuration with HB SM.

The parameters of the benchmark system considered in this study are listed in Table I. A detailed discussion of the system design for these parameters is discussed in our previous work [24], [25].

TABLE I
MMC Characteristics

Symbols	Item	Value
N_{min}	Minimum number of SMs	17
V_{dc}	Pole-to-pole DC voltage	17 kV
S_{n}	Rated power	10 MVA
V_{IGBT}	Withstand voltage of IGBT	1700 V
S_{f}	Safety factor of IGBT	0.65
E_{MMC}	Energy stored in the MMC	40 kJ/MVA
C_{SM}	SM capacitor	6.5 mF
f_{sw}	Switching frequency	177 Hz

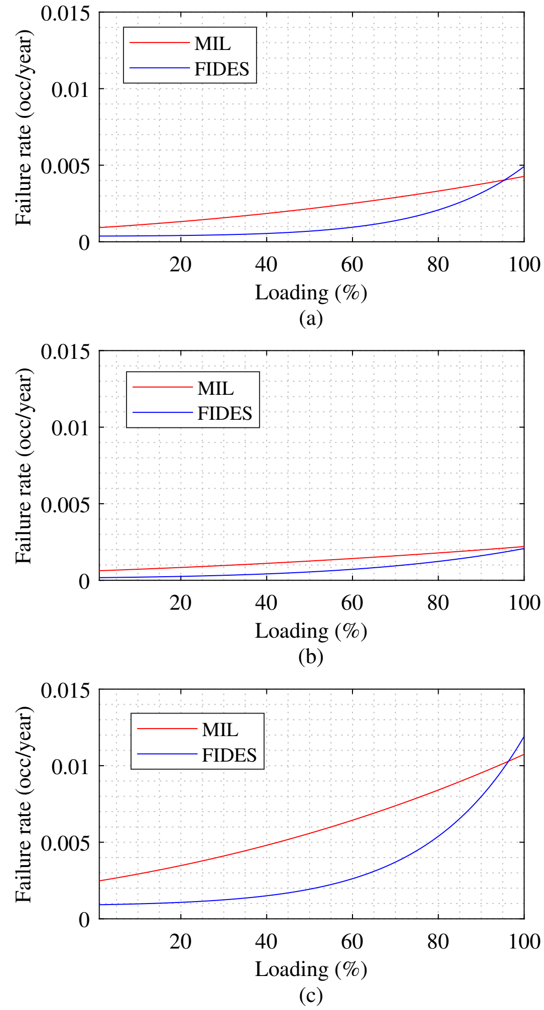

Fig. 2. Failure rate of (a) IGBT, (b) capacitor bank, and (c) SM with varying loading.

B. Failure Rate Estimation

1) MIL Handbook: The failure rate of IGBTs ($\lambda_{\text{MIL-IGBT}}$) and capacitors ($\lambda_{\text{MIL-Cap}}$) can be estimated using the MIL method as shown in (1) and (2), respectively [5].

$$\lambda_{\text{MIL-IGBT}} = \lambda_{\text{base-IGBT}} \pi_{\text{T}} \pi_{\text{S}} \pi_{\text{A}} \pi_{\text{R}} \pi_{\text{E}} \quad (1)$$

$$\lambda_{\text{MIL-Cap}} = \lambda_{\text{base-Cap}} \pi_{\text{T}} \pi_{\text{V}} \pi_{\text{SR}} \pi_{\text{Q}} \pi_{\text{E}} \pi_{\text{C}} \quad (2)$$

Herein, the base failure rates of both IGBT ($\lambda_{\text{base-IGBT}}$) and capacitor ($\lambda_{\text{base-Cap}}$) is assumed to be 0.000876 occ/year. Various correction factors (π_{xx}) are used to incorporate the impact of operational characteristics such as temperature (π_{T}), voltage (π_{v}) and other environmental as well as quality consideration. The specific assumptions are detailed in our previous work [7], [15] and are not repeated here for brevity.

2) FIDES: A more recent FIDES method [4] to calculate the failure rate of components (λ_{FIDES}) is compared with the reliability numbers for MMC with varying loads predicted with MIL. Unlike λ_{MIL}, λ_{FIDES} considers the technical control over manufacturing, field operation and maintenance, and physical failure. The model was developed based on the details described in [4] and not repeated here to keep the discussion concise.

It can be observed that while the failure rates are comparable for both methods at 100 % loading, FIDES has a lower failure rate as compared to MIL for lower converter loading. This has interesting consequences for the loading-dependent reliability of the MMC with incorporated redundancy, as discussed in subsequent sections. Fig. 2 shows the MMC's IGBT, capacitor, and SM failure rate for the considered assumptions with the MIL and FIDES method.

III. Redundancy Concept

Redundancy is applied as a fault-tolerant strategy to maintain normal operation without degradation after faults [19]. Various redundancy strategies have been explored in reference [11]. This article uses the active and standby redundancy strategies as follows.

A. Active Redundancy

Fig. 3 illustrates the MMC's reliability block diagram (RBD) that employs active redundancy. As presented in Fig. 3, the assumptions determining which components should be considered for reliability analysis can change the outputs according to [15]. However, in this study, only IGBT and capacitor banks are considered. With this approach, the quantity of functional SMs is consistently maintained at the minimum requirement of N_{min}. During operation, all SMs are energized, but triggering signals are sent only to N_{min} randomly chosen SMs, with all SMs taking turns. Triggered SMs can be either original or redundant [12]. If $N_{\text{red}} = n - N_{\text{min}}$ represents the number of redundant SMs in each arm, the reliability of the arm can be calculated using the k-out-of-n formula given by (3) [26].

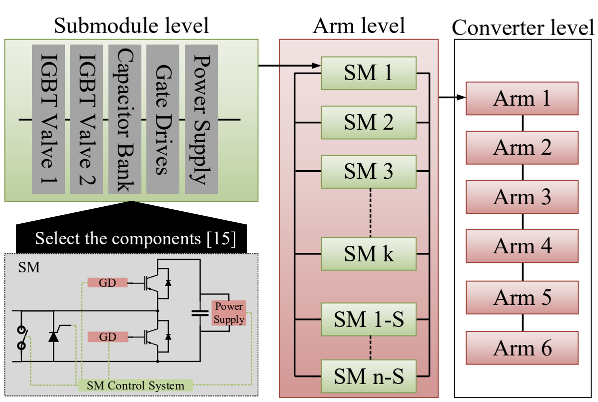

Fig. 3. The RBD of the MMC operating with active redundancy.

$$R_{\text{arm-A}}(t) = \sum_{N_{\text{min}}}^{n} C_n^{N_{\text{min}}} R(t)^{N_{\text{min}}} (1 - R(t))^{n - N_{\text{min}}} \quad (3)$$

$$R(t) = e^{-\lambda_{\text{SM}} t} \quad (4)$$

$$\lambda_{\text{SM}} = 2 \times \lambda_{\text{x-IGBT}} + \lambda_{\text{x-Cap}}, \rightarrow \text{x} \in (\text{FIDES}, \text{MIL}) \quad (5)$$

where λ_{SM} is failure of the SM with N_{min} operational SM.

B. Standby Redundancy

In standby, the redundancy strategy and the RBD of MMC with standby redundancy are presented in Fig. 4. In standby redundancy, the redundant SMs remain in idle mode, and when the first SM fails, the redundant SM starts to operate, and this chain of events takes place until there is no redundant SM left. As illustrated in Fig. 4, when in standby redundancy mode, the arm's reliability can be computed by utilizing the Homogeneous Poisson Distribution formula presented in equation (6), given that $N_{\text{red}} = n - N_{\text{min}}$ is the count of the spare SMs in each arm.

$$R_{\text{arm-S}}(t) = \sum_{i=0}^{n - N_{\text{min}}} \frac{(\lambda_{\text{s}} t)^i}{i!} e^{-\lambda_{\text{s}} t} \quad (6)$$

$$\lambda_{\text{s}} = (2 \times \lambda_{\text{x-IGBT}} + \lambda_{\text{x-Cap}}) \times N_{\text{min}}, \rightarrow \text{x} \in (\text{FIDES}, \text{MIL}) \quad (7)$$

Equation (7) defines λ_{s} as the failure rate of an arm with N_{min} functional SMs. As the MMC has six arms, its reliability can be computed using equation (8).

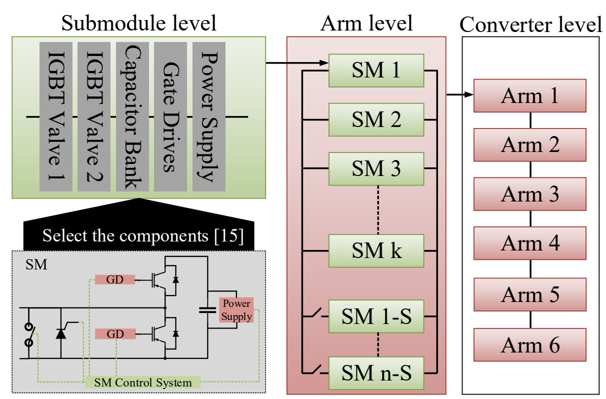

Fig. 4. The RBD of the MMC operating with standby redundancy.

$$R_{\text{MMC-x}}(t) = (R_{\text{arm-x}}(t))^6, \rightarrow \text{x} \in (\text{A}, \text{S}). \quad (8)$$

This study employs the percentage of the lifetime B_α as a gauge of equipment breakdown over time (9) defines this measure.

$$F_{\text{MMC}}(B_\alpha) = 1 - R_{\text{MMC}}(B_\alpha) = \frac{\alpha}{100} \quad (9)$$

where the unreliability function F_{MMC} is utilized to indicate the failure rate of the population. The design process involves using the B_{10} lifetime, which denotes the period within which 10% of the devices fail and the system's reliability will reach 90%. This information is then employed to determine the ideal count of redundant SMs. Fig. 5 illustrates the reliability assessment results performed on a 10 MW, 17 kV DC link voltage MMC with an annual average loading of 50%. The results presented are without considering the effect of redundancy. It is evident from the results that if the FIDES method is utilized to estimate the component failure rate, the predicted B_{10} lifetime is approximately 0.54 years. On the other hand, MIL estimates the B_{10} lifetime to be about 0.19 years.

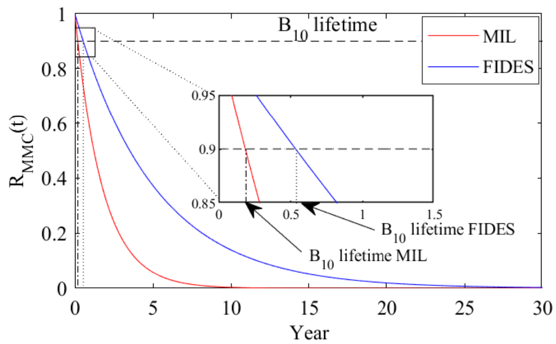

Fig. 5. Reliability results of 10 MW 17 kV DC link MMC with annual average of 50% loading for MIL and FIDES with no redundancy.

To assess the impact of redundancy, the results are further presented in Fig. 6 (a) and (b), considering the presence of one active and one standby redundant SM in each arm, respectively. As depicted in Fig. 6 (a), the application of active

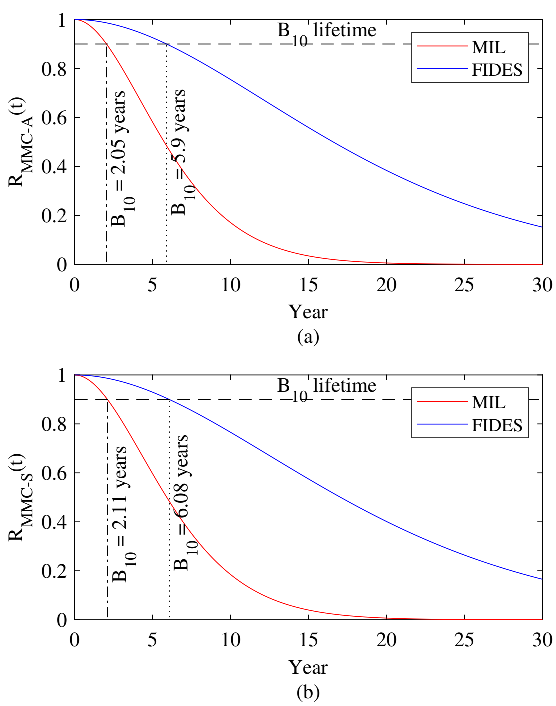

Fig. 6. Reliability results of 10 MW 17 kV DC link MMC with an annual average of 50% loading with one redundant SM in each arm for (a) active redundancy strategy and (b) standby redundancy strategy.

redundancy leads to an estimated B_{10} lifetime of 2.05 years and 5.9 years as determined by the MIL and FIDES methods, respectively. Conversely, standby redundancy results in B_{10} lifetime estimates of 2.11 and 6.08 years, as determined by the MIL and FIDES methods. The required lifetime of 10 years necessitates the use of additional redundant SMs. The number of redundant SMs necessary in each arm of the MMC to fulfill the 10-year lifetime requirement at 50% loading is depicted in Fig. 7.

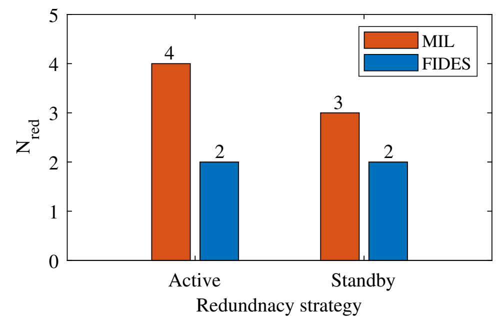

Fig. 7. Number of required redundant SM in each arm to meet B_{10} lifetime requirement of 10 years.

IV. Case-study for Cost, Reliability, and Efficiency-based

The reliability and cost of the MMC exhibit a trade-off, with the enhancement of reliability leading to an increase in cost. This section delves into the cost aspect of the MMC. The MMC's total cost encompasses capital expenditure (CAPEX) and operational expenditure (OPEX).

A. CAPEX

To evaluate the MMC's capital expenditures (CAPEX), the cost of the primary components is considered. These include power electronics components (such as semiconductors, power supply, and control systems) and capacitors. The anticipated capital cost of power electronics components (CI_{PE}) is computed using equation (10), as per [1]:

$$CI_{\text{PE}} = K_{\text{PE}} N_{\text{semi}} V_{\text{IGBT}} I_{\text{nominal}} \tag{10}$$

where I_{nominal} denotes the nominal current of the IGBT, which is 480 A. N_{semi} represents the total number of IGBT switches in the MMC and is equivalent to $N_{\text{semi}} = 6 \times 2 \times n$. Furthermore, K_{PE} represents the estimated cost of installed power and is valued at €3.5/kVA, as cited in [1]. Using these variables, the projected capital cost of power electronics components (CI_{PE}) can be estimated using equation (10). Additionally, the anticipated capital cost of capacitance (CI_{Cap}) can be determined through equations (11) - (14):

$$CI_{\text{Cap}} = K_{\text{Cap}} E_{\text{Cap}} \tag{11}$$

$$E_{\text{Cap}} = 6 \times n \times E_{\text{Cell}} \tag{12}$$

$$E_{\text{Cell}} = \frac{1}{2} C_{\text{SM}} V_{\text{SM}}^2 \tag{13}$$

where K_{Cap} is the estimated cost of installed capacitors which is €150/kJ [1]. The CAPEX of the MMC can be obtained from summing up CI_{PE} and CI_{Cap} given by (14).

$$CAPEX(€) = CI_{\text{Cap}} + CI_{\text{PE}} \tag{14}$$

B. OPEX

The operational efficiency of the MMC is determined utilizing the approach outlined in [12]. To estimate the switching and conduction losses of IGBTs, the technique explained in [24] is employed. The switching and conduction losses are evaluated for various load conditions. The yearly energy losses (E_l) are calculated using equation (15) in the following manner:

$$E_l = \int (100 - \eta(t_i)) \times P_{\text{MMC}} \tag{15}$$

where the efficiency of the MMC at a particular time t_i is denoted by $\eta(t_i)$, and P_{MMC} refers to the rated power of the MMC in MW. As a result, the operational expenditure (OPEX) can be approximated in the following manner:

$$OPEX(€) = K_o E_l \tag{16}$$

where K_o is the price per kWh and based on loss penalty for the transmission system, K_o = 0.11€/kWh is employed [1]. The normalized total cost of the MMC in €/kVA is estimated by (17)

$$Normalized\, cost = \frac{CAPEX + OPEX}{S_{\text{n}}}, (S_n \text{ in kVA}). \tag{17}$$

Fig. 8 presents a comprehensive evaluation of the economic aspects of the MMC, incorporating the CAPEX, OPEX, and reliability requirement (B_{10} lifetime of 10 years). The impact of varying annual average loading, ranging from 1 % to 100 %, is also presented. The results of the analysis reveal several noteworthy observations. Firstly, it is evident that implementing redundancy increases the cost of the MMC, which is contingent on the annual average loading. Secondly, utilizing the MIL handbook to estimate component failure rates results in a higher price for the MMC due to the requirement for additional redundant SMs, which affects both CAPEX and OPEX in the case of active redundancy. Lastly, adopting standby redundancy proves to be a cost-effective solution, particularly for higher annual average loading, as it results in similar OPEX compared to the case without redundancy while also providing improved reliability, thus reducing the number of redundant SMs and CAPEX.

V. Conclusion

In this study, the economic analysis of the MMC system demonstrated that the use of MIL leads to a higher value of the failure rate and, therefore, increases the overall cost of the MMC system. Moreover, the impact of redundancy was analyzed from both reliability and cost perspectives. When active and standby redundancies were applied, the results revealed MIL and FIDES' estimated B_{10} lifetime values. The study showed that redundancy plays a crucial role in determining the cost of the MMC system, which is dependent on the annual average loading of the system. The results indicated that applying standby redundancy can decrease the cost of the MMC, particularly for higher average yearly loading, by improving the reliability and reducing the number of redundant SMs required. The findings of this study highlight the delicate balance between reliability and cost in the design of MMC systems. The choice of failure rate estimation methodology (MIL, FIDES) and the type of redundancy applied can significantly impact the MMC's cost and reliability. The system's annual average loading should also be considered when making these design decisions. The insights gained from this study could aid in the development of cost-efficient and reliable MMC systems in the future.

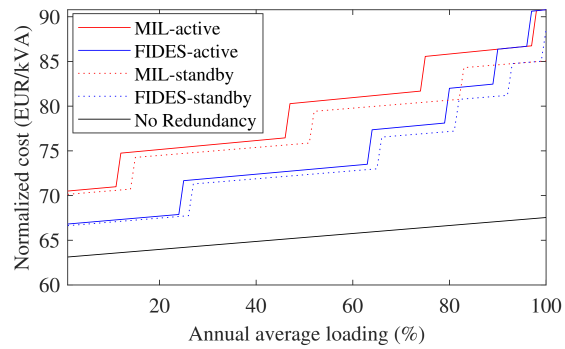

Fig. 8. Normalized cost of the MMC with different redundancy strategies under various annual average loading.

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