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Harmonic Resonances in Wind Power Plants: Modeling, Analysis and Active Mitigation Methods

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***Abstract*—This work reviews the state-of-the-art in the field of harmonic resonance problems in Wind Power Plants (WPPs). Firstly, a generic WPP is modeled according to the equivalent circuits of its passive and active components. Main focus is put on modeling active components, i.e. the ones based on power converters. Subsequently, pros and cons of frequency and time domain analysis methods are outlined. The next sections are devoted to mitigation methods implemented in the power electronics converters. From the wind turbine perspective, different techniques to enhance the robustness of the controller are analyzed. Subsequently, the suitability for active damping of harmonics using STATCOM devices is assessed, with focus both on control techniques and power converter technologies.**

***Index Terms*—Power conversion harmonics, power system harmonics, resonance.**

I. Introduction

Wind power plants (WPPs) are usually located in remote areas, where bigger wind resources are available. In remote areas, the short-circuit power tends to be small, so the term "weak grid" is usually associated to WPP. In this scenario, voltage regulation and power quality and stability phenomena become a challenge [1].

Electric resonance is one of the most challenging scenario for WPP operation. Resonance issues arise in WPPs because their circuits contain both inductive and capacitive elements, which interact with active components [2]. From the wind energy industry perspective, this poses a collection of practical problems which can be summarized as follows [3]:

- A certain harmonic voltage or current level may be unacceptable because it results in damage to equipment, mal-operation of equipment, loss-of-life-of-equipment or other practical concerns. E.g., resonances can cause stability problems in the closed-loop controllers of grid-connected converters.
- A second type of unacceptability occurs when the limits set in the main applicable standards, such as EN-50160, IEC $61000-2-2$ and IEC $61000-3-6$. Furthermore, the limits set by the transmission system operators (TSOs) in the grid codes should be considered.

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Therefore, WPP circuit analysis and modeling are an important topic of research in order to assess the most suitable mitigation techniques. The sections of this paper are then organized to consider firstly the origin of harmonic resonance issues and subsequently address active mitigation techniques.

II. Analysis Methods

A linear approach can be considered for frequency-domain based analyses [1], [4]–[7]. In this case, the WPP components are represented by their linear model, which may include passive components and ideal voltage/current sources. Frequency scan and harmonic power flow methods are included in this category [6]. Focusing on harmonic resonances, their frequencies correspond to the eigenvalues of the WPP circuit admittance matrix. Furthermore, overcurrent/overvoltage levels can be studied as a function of harmonic source placements [4]–[7]. A complex vector analysis (available in stationary and synchronous reference frames) is suitable to evaluate both positive and negative harmonic sequences [8]. In general, it can be stated that frequency-domain methods have a low computational burden and provide good assessments when the effect of active devices is not significant (e.g., at the transmission point of connection) [6].

However, frequency-domain analysis is not suitable for non-linear modeling. On the other hand, important phenomena is associated to non-linearities in the WPP circuit, such as core saturation in transformers [9], [10] (and generators in the case of WPP including type III wind turbines [11]), proximity and skin effects in high voltage transmission cables [12], [13] and PWM switching [6]. Time-domain based electromagnetic transient (EMT) simulation methods are better suited to assess non-linear models [1], [6]. Therefore, EMT simulation should be considered when the dynamics of the WPP (at some operation point) clearly depend on such non-linearities. EMT simulations are usually more resource-consuming than frequency domain studies [6].

III. WPP Circuit Modeling

Fig. 1 shows a generic WPP circuit. Matrix notation is used to represent the three-phase system. The whole system impedance/admittance matrix is available by modeling the

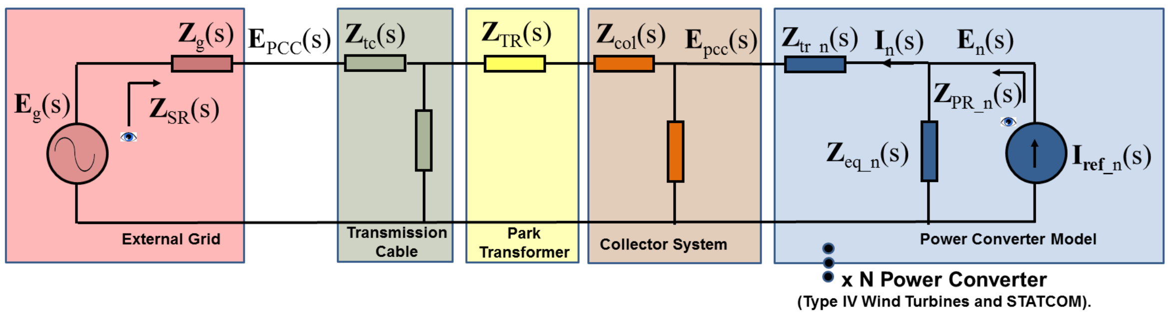

Fig. 1. WPP circuit modeling in the frequency domain. Sources and impedances are represented by vectors and matrices, respectively.

WPP components. As an example, some parallel and series resonances are also represented in Fig. 1.

- The series impedance, seen by the grid voltage source is $\mathbf{Z}_{SR}(s)$. Assuming a diagonal system, harmonic over-currents are likely at such frequencies that the non-zero elements of $\mathbf{Z}_{SR}(s)$ are small.
- Each current source (i.e. any power converter in the WPP) sees a parallel resonance matrix $\mathbf{Z}_{PR_n}(s)$ (with $i = 1, 2, ...$). Harmonic over-voltages [at $\mathbf{E}_{pcc_n}(s)$ point] are likely for such frequencies at which $\mathbf{Z}_{PR_n}(s)$ diagonal elements are high.
- In complex WPP, a parallel resonance can be seen as a series resonance at another point of the circuit.

Resonance phenomena arise in the transition between inductive and capacitive behavior, with resonances associated to low frequencies usually being the most problematic [2], [6]. E.g., in no loaded off-shore WPPs, low frequency resonances arises because the interaction between transformers (inductive) and cables (capacitive) [14] .

Many relevant aspects of the components depicted in Fig. 1, including non-linear modeling, are addressed in the following.

A. External Grid

The external grid is represented by its Theverin equivalent, which is defined by its impedance $\mathbf{Z}_g$ in series with the voltage source $\mathbf{E}_g(s)$. TSOs provide data to model the external grid in a wide range of scenarios [2].

1) Grid Impedance Loci: The value for the external grid impedance is provided in a grid impedance locus diagrams [2], [15], [16]. This representation bounds in sectors the potential values for $\mathbf{Z}_g(s)$ [2]. The impedance locus is specified for different groups for harmonics. E.g., *National Grid* provides one diagram for harmonics in the range $h = [2, 5]$ and another one for higher order harmonics up to the 17^{th} [17].

Since an impedance locus includes multiple combinations, the worst case scenarios are identified for detailed analysis. Worst cases are usually located in the boundaries [15]. A field method for grid impedance measurement is given in [16].

2) Background Voltage Distortion: The background voltage distortion [defined at $\mathbf{E}_g(s)$] represents a source of harmonics in the WPP circuit. The maximum values for different harmonic orders are given by the TSO and represented in % of the fundamental voltage [15], [17].

B. Transmission Cable

The transmission cable introduces resistive, inductive and capacitive effects. The significance of the transmission cable in the WPP circuit increases with the cable length [1], [14].

Cable suppliers provide data-sheets for frequency domain modeling [12], [18]. However, detailed layouts and field data measurements better reflect the cable models [14]. Low order (lumped) impedance models can be considered with high accuracy for some studies, such as current control assessment [14], [18]. However, distributed models are more accurate when studying harmonics over a wider frequency range [12], [18]. The modeling of non-linear effects, such as skin and proximity effects, requires the use of time-domain based electromagnetic transient (EMT) simulation tools [12], [13].

C. Power Transformers

The simplest linear model for the main park transformer is obtained through its leakage inductance $\mathbf{Z}_{TR}(s)$ and neglecting magnetization inductance and currents. However, it does not describe phenomena like core saturation (magnetizing currents) and iron losses [9]. The core losses can be modeled in a EMT simulations by updating the magnetizing reluctance as a function of the flux linkages [9], [10], [19]. Detailed EMT models permit to assess phenomena such as inrush current during wind turbine energization and grid faults, and non-linearities of the harmonic impedance [19].

D. Collector System

Equivalent representations of the WPP collector system are made to simplify power system modeling for future developments or planned expansions [20]. The MV cable system and other components such as capacitor banks and reactive filters contribute to the collector impedance $\mathbf{Z}_{col}(s)$. The collector topology has an influence on harmonic propagation [2]. An insightful case study for a large WPP is provided in [20].

E. Average Modeling of a Grid-Connected Power Converter

This section details how to obtain a simplified model for grid-tied converters working in the linear region. The simplified model provides a good approach of the current converter behavior as it is suitable to represent the converter impedance as seen by the other components of the circuit.

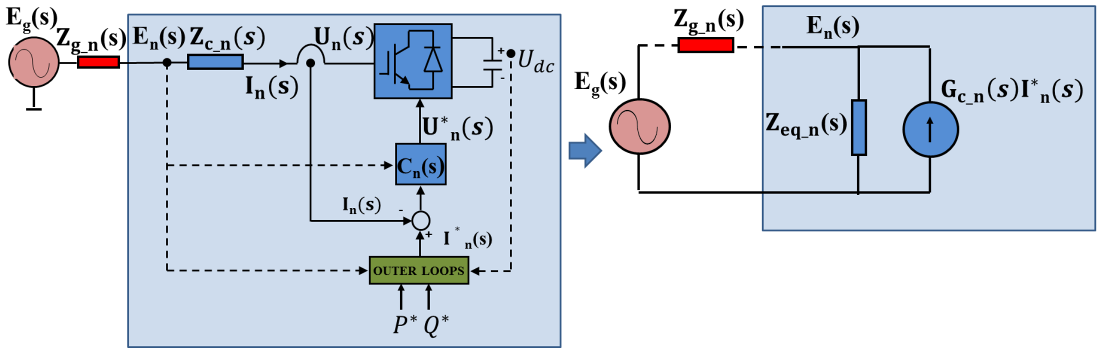

Fig. 2. Modeling of a Grid-connected power electronics converter in the WPP circuit (Fig. 1). Each converter sees its grid impedance $\mathbf{Z}_{\text{g\_n}}(s)$.

1) Derivation of the Model: The output current of the converter in Fig. 2 is given by

$$\mathbf{I}_{\text{n}}(s) = \mathbf{G}_{\text{c\_n}}(s)\mathbf{I}^*_{\text{n}}(s) + \mathbf{Z}^{(-1)}_{\text{eq\_n}}(s)\mathbf{E}_{\text{n}}(s) \quad (1)$$

with $\mathbf{G}_{\text{c\_n}}(s)$ being the closed loop transfer function and $\mathbf{Z}_{\text{eq\_n}}(s)$ the equivalent Norton impedance. These two parameters are obtained as follows. The grid current $\mathbf{I}_{\text{n}}(s)$ is given by

$$\mathbf{I}_{\text{n}}(s) = \mathbf{Z}^{-1}_{\text{c\_n}}(s)[\mathbf{E}_{\text{n}}(s) - \mathbf{U}_{\text{n}}(s)] \quad (2)$$

with $\mathbf{Z}_{\text{c\_n}}(s)$ being the converter output filter impedance and $\mathbf{U}_{\text{n}}(s)$ the output voltage. On the other hand, the converter control law is defined by

$$\mathbf{U}^*_{\text{n}}(s) = -\mathbf{C}_{\text{n}}(s)[\mathbf{I}^*_{\text{n}}(s) - \mathbf{I}_{\text{n}}(s)] \quad (3)$$

with $\mathbf{U}^*_{\text{n}}(s)$ being the PWM reference and $\mathbf{C}_{\text{n}}(s)$ the controller transfer function. If system delays (due to discrete-time operation) are neglected $\mathbf{U}_{\text{n}}(s) = \mathbf{U}^*_{\text{n}}(s)$, so the aimed expressions are obtained as follows

$$\begin{aligned} &\mathbf{G}_{\text{c\_n}}(s) = \mathbf{Z}^{(-1)}_{\text{eq\_n}}(s)\mathbf{C}_{\text{n}}(s) \quad \text{with} \\ &\mathbf{Z}_{\text{eq\_n}}(s) = \mathbf{Z}_{\text{c\_n}}(s) + \mathbf{C}_{\text{n}}(s) \end{aligned} \quad (4)$$

2) Physical Interpretation: For the sake of generality, the matrix expressions can be considered diagonal, which means that there is not cross-coupling between the vectors which define the three-phase system [8]. Using then a scalar nomenclature, some key aspects can be extracted from the model. The controller tends to have a high open loop gain at the low frequencies region [i.e. $\mathbf{G}_{\text{c\_n}}(s) \approx \vec{1}$ and $|\mathbf{Z}_{\text{eq\_n}}(s)| >> |\mathbf{Z}_{\text{c\_n}}(s)|$ in the control bandwidth], but it tends to behave as a passive component [i.e. $\mathbf{G}_{\text{c\_n}}(s) \approx \vec{0}$ and $\mathbf{Z}_{\text{eq\_n}}(s) \approx \mathbf{Z}_{\text{c\_n}}(s)$] at higher frequencies. It should be also noted that the sign criterion for current is selected so $\mathbf{Z}_{\text{eq\_n}}(s)$ is passive when the power converter is working in stable operation (see Fig. 2).

3) Bandwidth Constraints: The previous approach has been derived by assuming that there is not effect of the system delays. If considered

$$\mathbf{U}_{\text{n}}(s) = \mathbf{U}^*_{\text{n}}(s)e^{-sT_d} = \mathbf{U}^*_{\text{n}}(s)e^{-s1.5/f_s} \text{ (ZOH + PWM effects)} \quad (5)$$

with T_d and f_s being the system delay and sampling frequency, respectively [21]–[24]. In order to avoid the positive feedback (instability), the bandwidth of $\mathbf{G}_{\text{c\_n}}(s)$ is limited to $0.1f_s$ [23]. At the same time, f_s is limited by the PWM carrier frequency f_{pwm}. In a two-level VSC using a regular sampling PWM $f_s = f_{pwm}$ (single update) or $f_s = 2f_{pwm}$ (double update) [23]. Clearly, the former is preferred from the control perspective. An even more convenient relation between f_s and f_{pwm} can be achieved with multilevel converters [25]. On the other hand, commercial devices tend to reduce switching rates to control power losses [25], [26], so there is a clear tradeoff between control ability and power losses. Focusing on the modeling, it is clear that a good knowledge of the device is needed to accurately asses its achievable control bandwidth.

4) Features and Limitations of the Average Modeling: The proposed modeling is suitable to represent the power converter in the WPP as it represents its internal impedance as seen by the other components. Its main advantage is the simplicity for implementation. However, some limitations should be also considered: e.g., its accuracy will decrease as the power converter works in a non-linear region of the PWM operation (the gain of the PWM is lower than 1) [27]. The switching harmonics are neither represented, even though this should not have a high impact in resonance studies as switching frequencies tend to be high.

A detailed model of the power converter, including non-linear effects, can be obtained by dedicated EMT tools [28], [29]. Such a detailed operation is suitable to accurately represent many non-linear behavior of the power converter, such as PWM patterns representation [27]. However, this is at the cost of a higher computational burden. Therefore, in practice, the inclusion of detailed power converter models in complex power systems, such as WPPs, is not always feasible, and then simplified models are usually needed [1], [6].

IV. Active Damping for Resonance Rejection

A power converter connected to the grid with electrical resonance tends to instability if there is a positive feedback of the current controller at such frequency [22], [24]. Furthermore, relative stability criteria (i.e., stability margins) are also of high importance, since systems with low stability margins are usually associated to critical overcurrents/overvoltages [22], [30]. From the control design perspective, this objective can be formulated as a maximization of the stability margins in the range of frequencies of the current control, i.e., up to $f_s/2$. Relevant control techniques are in the following.

- The system resonance can be damped by using a derivative term in a voltage feed-forward path. This technique has been shown to be specially suitable when the range of frequencies to damp is low [22], [31].
- Virtual resistors are implemented by an extra current feedback path, which emulates the effect of a real resistor inside the control loop [32].
- Some techniques are based on a selective attenuation of the resonance components inside the control loop. The resonance frequencies are identified and then attenuated by notch filters [33].

The following linear control techniques are suitable for controller design with consideration of plant uncertainties.

- The sensitivity peak or vector gain margin is available from Nyquist diagram inspection. It is a very reliable stability margin, especially suited for system with resonant behavior [14], [30]. This permits to perform sensitivity analysis as function the grid parameters [14].
- The passivity design method permits to stabilize the power converter even the grid impedance $\mathbf{Z}_{\text{g\_n}}(s)$ (see Fig. 2) is unknown [22], [32]. This method aims to shape the converter admittance given $\mathbf{Z}_{\text{eq\_n}}^{(-1)}(s)$, so it is passive in the control range of frequencies limited by $f_s/2$.

A. Selective Harmonic Elimination PWM

As a part of the power converter control, selective harmonic elimination (SHE) PWM could be also considered at this stage. SHE-PWM algorithms avoid generation of low order harmonics due to the switching operation [34], [35]. Hence, SHE-PWM is suitable to avoid the excitation of power system resonances. SHE is achieved by a optimum (off-line) selection of switching modulation patterns, which strongly depends on the power converter topology (number of levels), modulation index and grid phase-angle [35]. Real time implementation of SHE-PWM algorithms is challenging as it requires complex techniques, such as the use of look-up tables with pre-calculated firing angles [35] or the implementation of time-dependent carriers [34].

V. Harmonic Resonance Damping by STATCOM

STATCOMs are included in many WPPs to deliver reactive power according grid-codes requirements [36], [37]. Therefore, the features of these devices are very suitable to be enhanced with active filtering (harmonic damping compensation). This section outlines the potential of these devices for active damping, specially focused on low order harmonics, as a very attractive alternative to bulky passive filters [38].

A. Active Filtering for Harmonic Resonance Damping

Shunt active filters for damping harmonic propagation has been successfully addressed at industrial level [39]. The parallel connected converter acts as a resistor (at selected harmonic frequencies inside the current controller bandwidth), so it damps the series resonances [39]. This is achieved by the following control action

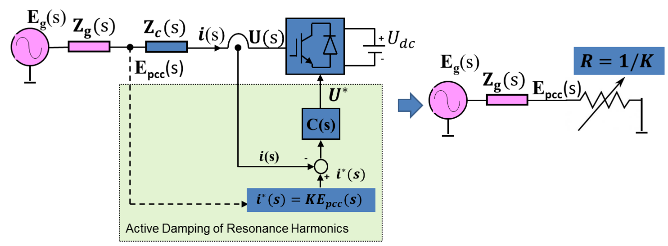

Fig. 3. Active harmonic resonance damping for STATCOM.

$$\mathbf{I}_h^*(s) = K_h \mathbf{E}_{pcc_h}(s) \tag{6}$$

with h being the harmonic order, and K_h ([1/Ω]) being the inverse of the "resistor" value at that component (set by a control parameter). $\mathbf{E}_{pcc_h}$ for damping specific ranges of harmonics can be extracted by signal processing and then perform a selective harmonic compensation [38], [40]. Fig. 3 shows a simplified STATCOM model, obtained when the control action is given by (6) and the current controller is considered ideal [$\mathbf{G}_{\text{c\_n}}(s) = 1$ and $\mathbf{Z}_{\text{eq\_n}}(s) = \infty$ as analyzed in the previous section]. However, as also previously discussed, the switching devices constrain the control/sampling frequency and hence, the achievable current controller bandwidth. Then, a more accurate modeling considering time-delays seems more suitable [22], [40].

In practice, active damping techniques will be limited in a relatively low frequency range of operation technique. Anyway, it should be reminded that active methods are more suitable for low order harmonics, as passive filters are more adequate for high frequency distortion [38].

1) Secondary Control for Remote Compensation: A potential shortcoming for the control arises if the STATCOM device is not connected at the point at which the voltage power quality is measured. In this case, the power quality enhancement can be based on secondary control structure [41], [42]. The voltage measurements at the PCC are provided to the compensating device through a low bandwidth communication. Then, at the power converter, a secondary controller implements a feedback structure which sets the voltage distortion according to some reference levels [41], [42]. The main shortcoming of this structure, is that the time constant of the secondary control is long in comparison to classical technique previously explained, as it depends on the communication time delay.

B. Power Converter Topologies

STATCOMs are usually included in the WPP circuit to deliver reactive power to support the grid voltage and fulfill grid-codes [36], [37]. Different power converter technologies are available, as summarized in Table I. The main advantage of LV technology is the power switching technology is mature and provides good performance with the simple 2L-VSC topology (low cost, high switching rate, etc). However, as installation power increases, the cost associated to installation

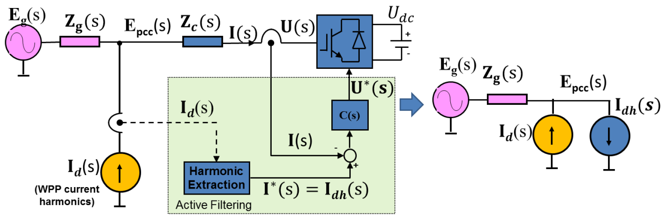

Fig. 4. Parallel active current filtering.

of many LV modules tends to increase, mainly to the need of bulky transformers and inductance filters. Multilevel MV topologies offer a better power density than LV devices, which sounds as an important feature as the WPP size increases [26]. With this perspective, power devices such as the press-pack IGBT modules have been developed to suit with multi-level MV topologies, with the Neutral Point Clamped Three Level (3L-NPC) topology being the most adopted by many manufactures [43]. In order to a higher reduction of bulky components, high voltage high power converters are gaining popularity for STATCOM applications. In this case, modular multilevel converter (MMC) topologies are the basic of the technology [44], [45]. Another advantage of HV topologies is that they offer more flexibility to be placed at many points of the WPP circuit.

TABLE I
AVAILABLE STATCOM TECHNOLOGY FOR WPP

Topology	**2L-VSC**	**3L-NPC**	**MMC**
Voltage Level	$\leq 690\,\mathrm{V}$	$[1.2, 4.5]\,\mathrm{kV}$	$[4.5, 69]\,\mathrm{kV}$
$S_{\textbf{per module}}$	$\leq 1\,\mathrm{MVA}$	$[\leq 1, 60]\,\mathrm{MVA}$	$[50, 100]\,\mathrm{MVA}$

C. Active Current Filtering

Another potential functionality for the WPP is given by active filters for current harmonic compensation [38]. The digital control basics are depicted in Fig. 4 and summarized in the following. Firstly, the instantaneous distorted current $\mathbf{I}_d$ is measured. Then, by a signal processing algorithm the harmonic currents are identified [46], [47]. These harmonic currents feed the current controller which should assure steady-state tracking. With this purpose specific harmonic controllers, such as the ones based on resonant filters, should be implemented [32], [48]–[50]. The implementation of parallel current active filtering in the wind turbines power converter have been also proposed as a method to compensate for non-linear harmonics generation in the WPP [51], [52].

VI. Hybrid Active Filters

Hybrid active filters can be also consider to enhance the harmonic filtering of the WPP. Hybrid active filters are a combination of passive and active filters, where the passive filter acts as a VSC impedance [38], [53], [54]. The passive filter is tuned so it absorbs the harmonics at which it is tuned, usually the lowest and more significant ones. Then the digital controller of the VSC, compensates for current harmonics [38], [53] or compensates the system harmonic resonances [54]. The VSC control technique for harmonic resonance damping is similar to the one explained in the previous section. The advantage of the hybrid filters is that the active part (VSC) can be rated very low in power and dc-link voltage, which permits to have a high bandwidth VSC [38], [54].

VII. Conclusions

This paper reviews many aspects of the state-of-the-art about harmonic resonances issues in WPPs. Firstly, some discussion about analysis methodology is provided: frequency domain techniques provide a good overview of the WPP circuit and it is useful for control design; however, non-linear analysis is needed to accurately represent some specific scenarios. Subsequently, key references for linear and non-linear modeling of the WPP circuit components are discussed. Among them, a simplified linear modeling for the power converter is provided. Its features and limitations of the average modeling are discussed. The next section is devoted to active damping control techniques to enhance the robustness of the power converter in the presence of harmonic resonances. Section V is devoted to the harmonic resonance damping technique by means of dedicated STATCOM device. Firstly, it is discussed how to include the harmonic damping feature in the STATCOM device. Subsequently, the existing STATCOM topologies are analyzed: one interesting outcome of this analysis points to MMC technology, which permits to handle with high voltages, high power and relatively high bandwidth at the same time.

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