Design and Realisation of Over-voltage Protection in Push-pull Inverters

Milomir Šoja, Slobodan Lubura, Dejan Jokić, Milan Đ. Radmanović

Abstract—**In this paper are presented our research results about possibility of use different types over-voltage protection circuits in push-pull inverters. We first analyzed the conventional passive type RC and RCD over-voltage protection circuits and gave experimental results. After that we analyzed active over-voltage protection circuit, made design of protection circuit components and provided experimental results. Final investigation has shown that active over-voltage protection is better solution than passive protection circuits with respect to efficiency and reliability.**

Index Terms—**Passive RC I RCD over-voltage circuit, active protection circuit, push-pull inverters.**

I. Introduction

INCREASE in share of renewable energy resources in total energy balance resulted in wider application of energy electronics inverters in power supply systems. Converters, which are part of power supply systems with renewable energy resources are power inverters in push-pull inverters. Topology of push-pull inverters is interesting for a number of reasons: existence of energy transformer for galvanic separation of input and output, simple modification of output voltage by its value and use of minimal number of switch components. Bearing in mind that design of such components always entails efficiency and reliability as performance criterium, use of minimal number of components is often crucial factor in favor of use of push-pull inverters as topology in power inverters.

Besides the above mentioned, one of the crucial factors that influences reliability of energy electronics is over power and over-voltage protection of switches used in the inverter. In the concrete case, in order to achieve reliable operation of push-pull inverter, it was necessary to design over-voltage protection that protects the switches from voltage peaks created by various parasite components of energy transformer and other elements of the energy circle of the push-pull inverter. The first step in realization of over-voltage protection is construction, and it entails minimizing the number of parasite components by minimizing switching power loops. In bridge inverters this procedure alone is in most cases sufficient if it is performed correctly, but because of topology of push-pull inverters other methods for decrease of over-voltage have to be applied. Several types of over-voltage protection have been described in literature, and they can be generally divided into three categories: passive dissipative, passive non-dissipative and active over-voltage protection. Passive RC and RCD type protections are the simplest. Basic shortcomings of this type of protection are energy dissipation and complexion of calculations because for making the right choice in protection components it is necessary to know parasite components of L_σ and C_σ energy circuit, which is very complicated to determine and it is also not uniform.

Second type of over-voltage protection is not dissipative in nature which gives it upper hand, but it demands extra accumulative components, which take over energy from parasite components and it all leads to larger dimensions of the device.

Third type of protection applied in practice is active protection which contains some active elements alongside to the passive ones. Described active over-voltage protection in push-pull inverters with adjusted trigger level turns on both energy switches at the same time which creates power switching loop in which energy that was building up in parasite components dissipates. In this manner over-voltage in switches is avoided. That means that powerful semi-conductive switches protect themselves from over-voltage.

In the first part of this paper is provided overview of some conventional over-voltage protection designs in push-pull inverters. In the second part is described active over-voltage protection. Experimental results are provided for all types of protection. Conducted research showed advantage in use of active over-voltage protection to the passive one.

II. TWO PARALLEL PUSH-PULL INVERTERS

The inverters with lower input voltage and power load above 1000 W frequently used topology of two parallel push-

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pull converters (2PP) [6] [7]. Fig. 1. shows the scheme of the above mentioned inverter that was used for testing different configurations of over-voltage protection circuits, and Fig. 2. shows manner of forming inverter output voltage wit output

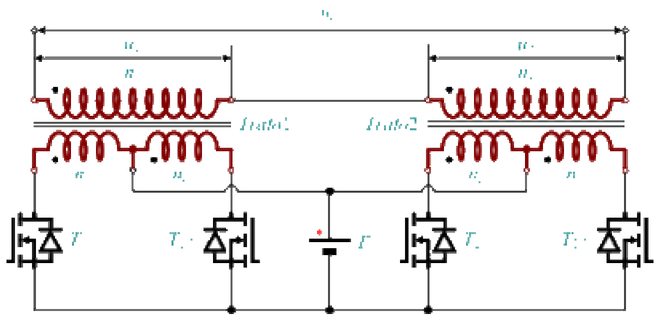

Fig. 1. Two parallel push-pull inverters.

voltage time shifts for individual push-pull inverters.

Each push-pull inverter forms square voltage by alternating conducting of corresponding switches, and "*quasi-sinus*" output voltage is formed by shifting the formed square

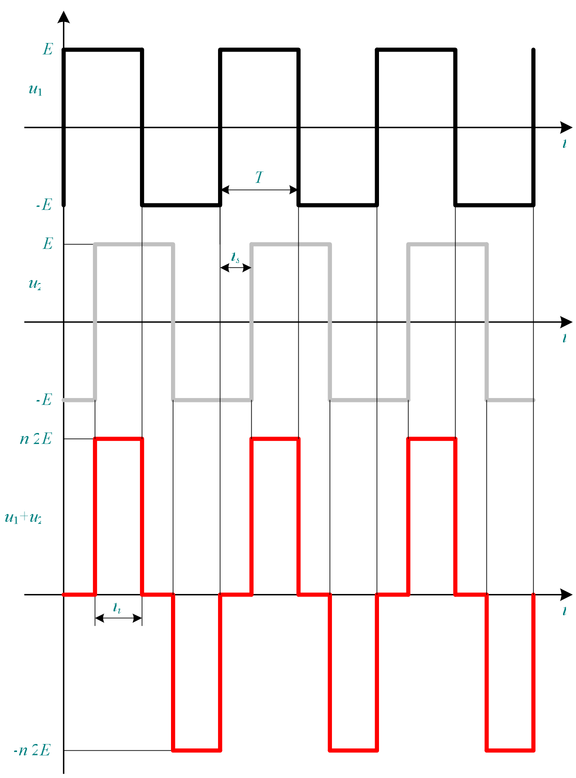

Fig. 2. Formation of output voltage ("quasi-sinus") in two parallel push-pull inverters.

voltages, as provided in Fig. 2.

It is obvious that two switches in the presented configuration are always turned on, while over-voltages are created in the other two in the moments of their switching off, and the over-voltages are superposed with double value of battery voltage because of push-pull inverter's nature of operating.

Typical wave shape of voltage on one switch of the push-pull inverter from Picture 1 in the moment of switching on without over-voltage protection with input voltage of couple of volts (2-3 V_{DC}) is shown in Fig. 3.

During the switching, power is moved from one to the other half of primary coil, which demands strong magnetic bond between primary coils in order to reduce built up energy in dissipative inductivity that causes over-voltage on switches while turning them off.

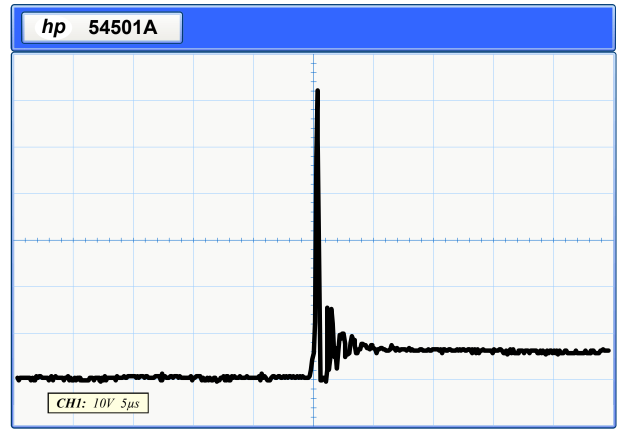

Fig. 3. Over-voltage on a switch at the moment of switching off in V_{BAT}=2-3 V_{DC}.

Standard manner of reducing over-voltage on switches is passive RC/RCD protection of dissipative or non-dissipative type.

III. OVER-VOLTAGE PROTECTION CIRCUITS

Basic function of all passive over-voltage protections is energy "absorption" of parasite components L_σ and C_σ of inverter energy circuit, which completely or partially eliminates over-voltage on switches. Capacitors that are connected in parallel with the switch are used for "absorption" of energy in these protections. If the energy of this capacitor dissipates on resistor then we say that we are talking about dissipative passive over-voltage protection. Non-dissipative passive over-voltage protection is also mentioned in [5] where energy of capacitor is transferred to input or not that frequently to output of power inverter by additional reactive components. Conducted research that is described in this paper gave answer to question of modes of application and performances of passive dissipative protections in push-pull inverters for protection of power switches.

A. RC protection

Fig. 4. shows way of connecting RC protection to switches of push-pull inverter.

Calculation of RC protection elements is rather complex because of not knowing exact values of parasite elements of individual inverter components, so in practice more simple methods are used for determination of values of components R and C protection. In order to create attenuation of oscillations in resonant circuit that is formed by parasite components of energy transformer L_σ and C_σ and energy switch (MOSFET) C_{DS} it is usually taken in push-pull inverters that $C>C_{DS}$. As initial value of capacitor C in [1] is recommended C=2-3*C_{DS}, and for R initial value can be selected according to nominal power of inverter I_O reduced to primary side of transformer and battery voltage E according to the following expression:

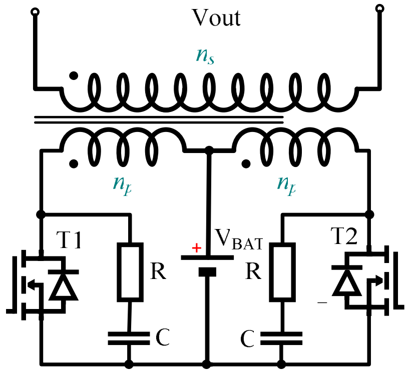

Fig. 4. Scheme of RC protection of push-pull inverter.

$$R = \frac{2E}{nI_O}, \tag{1}$$

Power that is dissipated on resistor R in RC protection with maximum power value on capacitor C is:

$$P_R = 2CE^2 . \tag{2}$$

As the energy dissipates in capacitor charging and emptying medium power value of power dissipated on resistor R is provided in the following expression:

$$P_{DIS=} 4CE^2 f_s , \tag{3}$$

where f_S is inverter switching frequency.

Wave shape of switch voltage in inverter from Fig. 1. with nominal load is shown in Fig. 5.

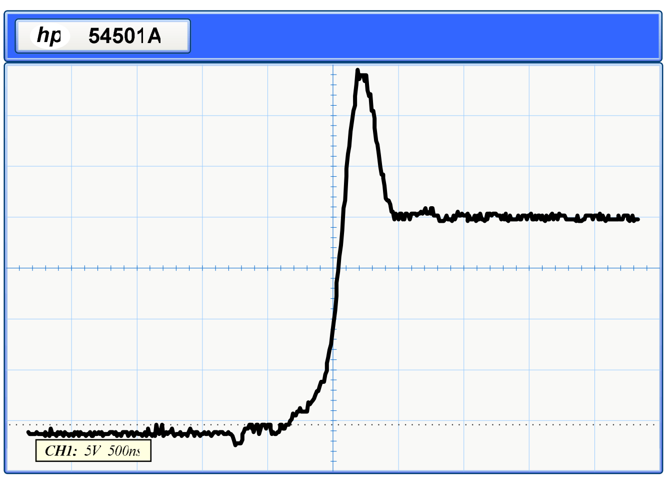

Fig. 5. Switch voltage in push-pull inverter.

B. RCD protection

It is obvious that two RC switch protections are necessary in push-pull inverters, which additionally complicates design of the device.

Unlike the above mentioned type of RC protection, this type of protection is in class of polarized protections and its mode of operating is completely different than the one we described earlier. The first step in designing RCD protection is determination of voltage increase time on the switch at its maximum current I_{Omax} as well as maximum allowed voltage value on capacitor C. Connection between current and voltage in the capacitor is provided in the following expression:

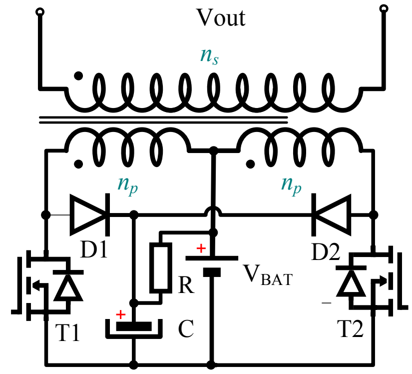

Fig. 6. RCD protection scheme.

$$I_{O\max} = C\frac{\Delta v_C}{t_r}, \tag{4}$$

where: $I_{O\max}$ - maximum switch current, Δv_C - change of voltage in the capacitor, t_r - switch voltage increase time.

Necessary capacitor value in over-voltage RCD depends on the value of parasite inductivity of energy circle L_σ and it can be determined according to the energy balance:

$$W_L + W_{C1} = W_{C2}, \tag{5}$$

where: W_L - built up magnetic energy on parasite inductivity L_σ, W_{C1} - initial capacitor energy in over-voltage protection, W_{C2} - total capacitor energy. Equation (4) can be written in the following form in case of push-pull inverters:

$$\frac{1}{2}LI_{O\max}^2 + \frac{1}{2}C(2E)^2 = \frac{1}{2}C(2E+\Delta V)^2 . \tag{6}$$

From the previous equation it is possible to determine capacitor C value for previously set value of over-voltage on switch ΔV :

$$C = \frac{LI_{O\max}^2}{4E\Delta V + \Delta V^2} . \tag{7}$$

Fig. 7 shows voltage wave shape on the switch of the push-pull inverter with RCD protection.

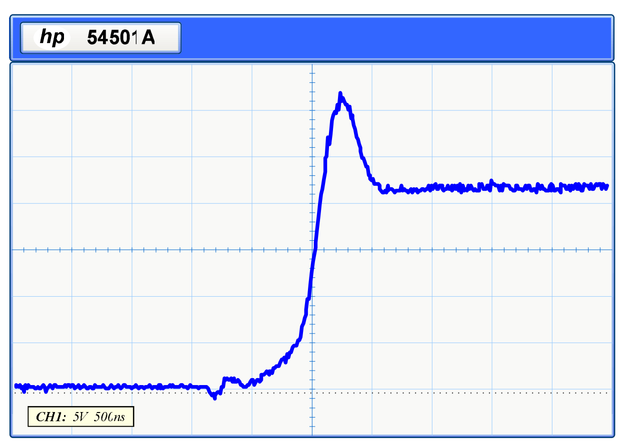

Fig. 7. Voltage on the switch of unloaded inverter.

C. *Active protection*

As we have mentioned earlier, basic problem in application of previously mentioned protections is complex calculus of the components that create the protection (they often have to be determined experimentally), difficulties in construction and additional losses that appear in the protection components.

All of these difficulties can be overcome by use of active protection. Scheme of active protection is provided in Fig. 8.

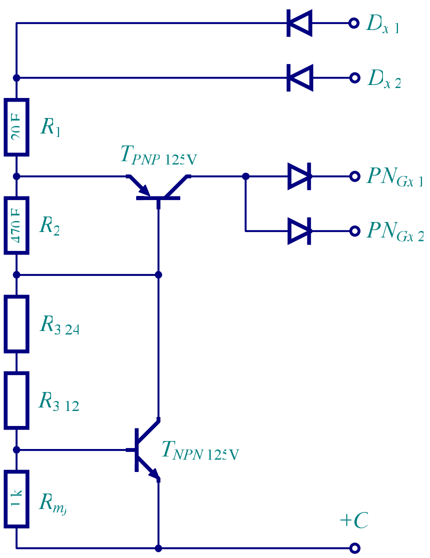

Fig. 8. Active protection scheme.

Operation of the presented protection comes down to active monitoring of the voltages between transistor drains in push-pull inverter (ports $D_{x.1}$, $D_{x.2}$) in relation to power supply voltage (voltage on input positive terminal of electrolyte capacitor +C). If the voltage between any MOSFET drain and input power supply is greater than protection trigger level voltage, it is conducted through transistors $T_{NPN.125\text{V}}$ and $T_{PNP.125\text{V}}$, switching on both powerful switches in push-pull inverter through $PN_{Gx.1}$ i $PN_{Gx.2}$. In that manner is used all the magnetic energy that accumulated in transformer parasite inductivity L_σ which caused over-voltage and power switches are hence protected.

With regard to the fact that both transistors and diodes which form active protection belong to the signaling components (block voltage should not be ≥100 V), and resistance is 0.25 W, it is obviously very cheap solution with practically no dissipation and which is without any difficulties possible to be fit in the energy part of inverter during the construction process.

Trigger level of the active protection is usually chosen by making maximum voltage on the power switch 10-25% greater than "normal" double DC input voltage.

$$V_{DS.\max} = 2 \cdot k_{VDS.\max} \cdot U_{bat.\max} = [1.1-1.25] \cdot 2 \cdot U_{bat.\max} . \quad (8)$$

Protection trigger level can also be determined according to the following expression:

$$\begin{aligned} V_{prag} &= V_{DS.\max} - V_{bat.\max} = (2 \cdot k_{VDS.\max} - 1) \cdot V_{bat.\max} , \\ V_{prag} &= [1.2-1.5] \cdot V_{bat.\max} \end{aligned} . \quad (9)$$

Once adjusted, trigger level remains constant and it does not depend on battery voltage. On the other hand, transistor voltage V_{DS} which turns on the protection depends on the battery voltage and it shifts within the boundaries of its change, which is acceptable. In order to simplify the calculation procedure for the resistor network it is agreed that the current through resistors $I_{\Sigma R.\max}$ is equal to 0.5 mA, at the moment the protection switches on. Resistor R_1 limits the current $T_{NPN.125\text{V}}$ and its value is usually 20 Ω. Voltage drop on resistor R_2 should be less than V_{be}≈0.6 V, and its value is 470 Ω.

Resistor R_{mj} determins protection trigger level and it is calculated from the following condition:

$$R_{mj} \cdot I_{\Sigma R.\max} = V_{be} \approx 0.6 \text{ V} , \quad (10)$$

which results in:

$$R_{mj} = \frac{V_{be}}{I_{\Sigma R.\max}} = \frac{0.6 \text{ V}}{0.5 \text{ mA}} = 1.2 \text{ k}\Omega .$$

Agreed R_{mj}=1 kΩ. Lower R_{mj} resistor value is agreed than the calculated one because transistor trigger level is not strictly defined and conductivity can start at slightly lower voltage.

Resistor R_3 should be adjusted in such manner that besides agreed values of other resistors it also defines current $I_{\Sigma R.\max}$ at the moment protection starts to operate (0.5 mA).

$$\frac{V_{prag}}{\Sigma R} = I_{\Sigma R.\max} = 0.5 \text{ mA}, \quad \Sigma R = R_1 + R_2 + R_3 + R_{mj}$$

$$(11) \quad \begin{aligned} \Sigma R &= \frac{(2 \cdot k_{VDS.\max} - 1) \cdot U_{bat.\max}}{I_{\Sigma R.\max}} \\ \Sigma R &= 2000 \cdot (2 \cdot k_{VDS.\max} - 1) \cdot U_{bat.\max} \end{aligned}$$

$$(12) \quad \begin{aligned} R_3 &= \Sigma R - (R_1 + R_2 + R_{mj}) \\ R_3 &= 2000 \cdot (2 \cdot k_{VDS.\max} - 1) \cdot U_{bat.\max} - (R_1 + R_2 + R_{mj}) \end{aligned}$$

(13)

Fig. 9 and 10 show dependence of change in resistor R_3 from demanded overvoltage on the transistor ($k_{VDS.max}$), for two battery voltages 12 and 24V_{DC}.

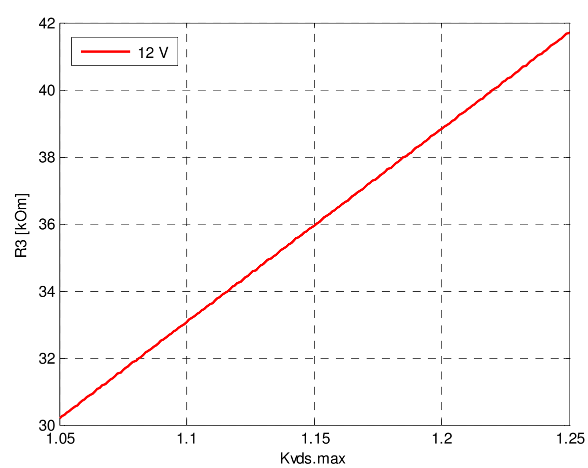

Fig. 9. Dependence of R_3 from allowed overvoltage on the switch ($k_{VDS.max}$) for U_{bat}=*12 V*.

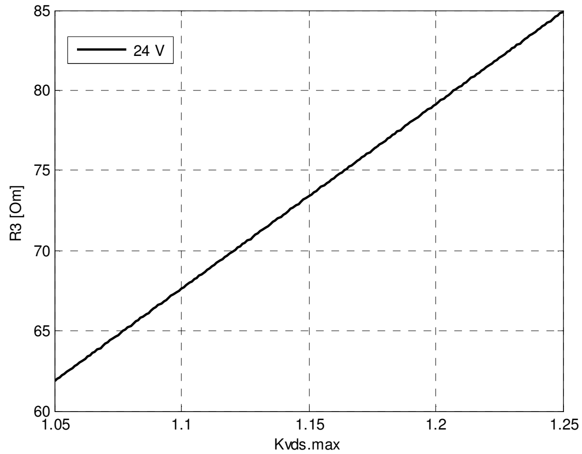

Fig. 10. Dependence of R_3 from allowed overvoltage on the switch ($k_{VDS.max}$) for U_{bat}=24 V.

IV. ACTIVE OVER-VOLTAGE PROTECTION EXPERIMENTAL RESULTS

Efficiency of suggested active protection was tested on power inverter realized as 2PP converters in parallel operating mode of nominal power 2000 W (Fig. 1.). Fig. 11. shows voltage on switches of one branch of push-pull inverter functioning as power supply voltage. Different voltage values on switches as result of changes of test battery voltages from 6 V to 24 V_{DC}. As it was previously mentioned, switch voltage is equal to sum of trigger level voltage of the active protection and battery voltage. Consequently, if we increase battery voltage, voltage on the switch also increases. Fig. 12 shows voltage of one branch of push-pull inverter under different inverter loads. When we compare voltage wave shapes on the switches for all types of protection we described (Fig. 5., 7. and 12.), it is obvious that active over-voltage protection gives the best results and that it provides the possibility that size of over-voltage does not depend on maximum current through the switch as it is the case with all other described types of protection.

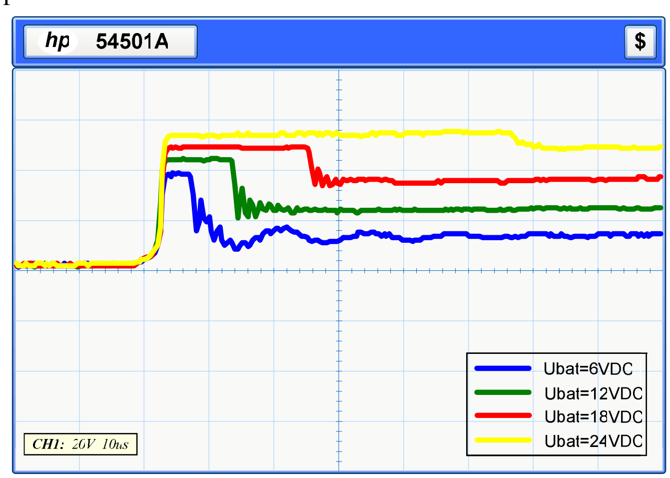

Fig. 11. Voltage wave forms on the drain of MOSFET with different input voltage values.

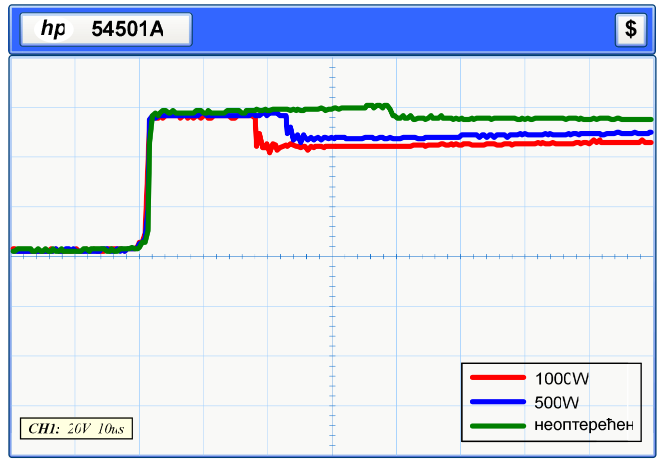

Fig. 12. Voltage wave forms on the drain of MOSFET under different inverter loads.

V. CONCLUSION

This paper presents results of research about application possibilities of different over-voltage protection types in push-pull inverters. We first analyzed conventional passive RC and RCD passive over-voltage protections and we provided experimental results. Then we analyzed active over-voltage protection and we provided calculations of protection components and experimental results. Conducted research resulted in conclusion that active over-voltage protection presents better solution than passive ones from the aspects of efficiency and reliability of the device.

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