Time Domain Signature Analysis of Synchronous Generator under Broken Damper Bar Fault

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Abstract—**Fault detection of electrical machines can avoid unplanned outage of the electricity generation at a power plant. Research related to a different type of faults in the synchronous generator, the broken damper bar (BDB) fault attracts less attention due to the low statistical population. However, a comprehensive condition monitoring system requires a method to diagnose this few in number faults also. Detection of BDB fault is difficult since damper bars are active only during a transient period, which could be start-up intervals or as a reaction to power system dynamics. In this paper, the BDB fault is detected during the machine start-up. The Radius of Gyration (RG) was introduced using a time series data mining (TSDM) approach that was applied to induced electromotive force of the rotor field winding due to BDB fault. Location and number of BDBs effect on the nominated feature are also studied.**

Index Terms—**broken damper bar, electromotive force, fault detection, finite element modeling, gyration radius, salient pole synchronous generator, time series data mining.**

I. Introduction

An unplanned outage of energy production centers (power plants) and production lines are one of the most critical concerns in the electric power industries. Energy production systems in large scale entirely depend on large electrical machines, especially synchronous machines. Large synchronous machines are one of the expensive equipment in the power plant. In addition, their maintenance and repair are costly, and any termination of the synchronous machine from the network due to fault leads to economic loss. Today, periodic maintenance systems are used in most industries related to electrical machines [1].

The newest predictive maintenance system, is an approach, which can detect faults in the rotatory electric equipment at an early stage. This method can increase the reliability of the system since it can avoid unplanned interruption of the electrical machines by providing continuous tracking of their status. In other words, the condition of the electric machine is evaluated online. Artificial intelligent systems send an alarm to operators to take appropriate actions as soon as the first sign of defects in the electric machine has emerged. This could prevent fault progress. Failure in the electrical machines, based on their severity, can be divided into two categories:

- Defects which are the gradual deterioration of the various components of the electric machine, which in time results in a fault if it is not eliminated.
- The fault has a high potential that occurs very quickly and leads to the outage of the equipment.

In general, faults can occur due to external factors such as severe short circuits in the power grid or internally due to gradual defects. Rapid response to the fault is the responsibility of the protection system. The protection system uses voltage, current profile, or extracted data associated with them at the terminal of the stator. It can subsequently disconnect the electric machine from the power system based on measured data in order to protect it against fast and destructive faults. However, the protection system can not detect the gradual defect inside the machine that leads to sub sequential faults. It is, therefore, necessary to have a condition monitoring system to perform the task.

The research related to BDB and end rings faults in large salient pole synchronous generators (SPSGs), have been limited, because the statistical population of this fault in comparison to other types of faults are low. Damper bars are used for synchronization of SPSG and quick response transients. In addition, damper bars protect the rotor winding during short circuit fault in stator bars. BDB fault in synchronous machines could occur due to the inadequate solid connection between the damper bar and the end ring. Current density in adjacent bars of BDB is increased even in the case of small fracture. The current of BDB flow through adjacent damper bars that lead to excess ohmic losses and consequently temperature rise. Thus, BDB fault causes hot spot around adjacent bars, which in turn increase the fracture speed of the neighboring bars.

The stator current is used to detect BDB fault in [2]. Harmonic components of the current are introduced to detect a fault as in:

$$(k * f)/p \tag{1}$$

where f is the stator frequency, p is the number of pole pairs, and k is an integer. It is shown that BDB fault gives rise to the amplitude of some current harmonics. The nominated index has a harmonic component of 30, 90, 150 and 180 Hz [2]. The sensitivity of the harmonic component of 30 Hz is higher than the other harmonic components at the presence of BDB fault. It should however be noted that the 30 Hz harmonic component in the line-to-line current of the SPSG is also sensitive to eccentricity and short-circuit faults. In other

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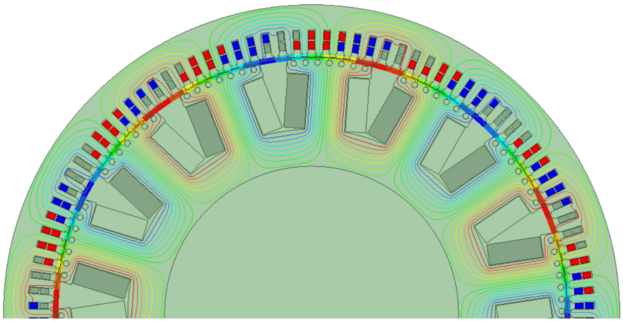

Fig. 1. 2-D modeling of SPSG using FEM

TABLE I
100 KVA/ 90KW, 14 POLES, 400V, 428 RPM, SALIENT POLE SYNCHRONOUS GENERATOR

Quantity	*Values*	*Quantity*	*Values*
Stator outer diameter	780 mm	Stator inner diameter	650 mm
No. of slots	114	No. of damper bars/pole	7
No. of turns	8	No. of turns / pole	35
Length of stack	208	Damper bar diameter	7.3mm
Widths of pole shoe	108mm	Widths of pole body	50mm
Widths of stator tooth	8.5mm	Height of stator tooth	29.5mm

words, it is not possible to detect BDB fault only based on this feature.

A pumped storage machine under BDB fault was studied in [3]. The required electromagnetic torque during the machine start-up is partly provided by the currents through the damper bars. The magnetic flux density of the machine was studied under faulty condition. It was shown that BDB fault causes an asymmetric magnetic field. Additionally, the start-up time of the machine under the faulty condition was also investigated-and proven to increased due to the fault. Nevertheless, start-up time is not a suitable indicator to diagnose BDB fault, because many factors could affect the machine start-up time such as misalignment, eccentricity faults, or load condition.

Damper bars of synchronous motors are used for synchronization and damping purposes until the rotor reaches synchronous speed. Therefore, the characteristic of the synchronous machine is similar to the induction motor prior to synchronization. Like induction motors, side-band harmonic components near the main frequency are subjected to change under the faulty situation. The left side-band component of the principal harmonic decreases from 50Hz to close to zero and then increases to the main frequency under a BDB fault during start-up time, which shapes the V form curve described in [4]. The Hilbert Huang Transform (HHT) is applied to the current signal of the synchronous machine. The Intrinsic Mode Function (IMF) component of the HHT includes main harmonic and harmonic component under 50 Hz. Consequently, the IMF component under BDB fault should show V shape curve that could indicate the faulty condition. It is noteworthy that; the magnitude of the left side-band of the main harmonic completely depends on the location, number, and the shape of the bars. In other words, there is a possibility of a reduction of the left side-band harmonic under the broken damper bar condition instead of an increase [4].

The end ring currents of the synchronous motor under BDB fault were investigated using Fast Fourier Transform (FFT) [5]. BDB fault gives rise to harmonic components in the end ring current spectrum. In this method, a current sensor is installed in the rotor pole. Another current sensor should be installed precisely 180 mechanical degrees opposite the pole in order to increase the accuracy of the measurement. This method is complicated and requires wireless data transfer equipment.

In the steady-state condition, the amplitude of the current that passes through the bars are low, which make BDB fault detection difficult. In [6], the synchronous generator was loaded under unbalanced load up to 25 percent that causes a negative sequence current in the damper bars. Due to the rotor poles polarity, two windings which are in series is required. An additional slip ring was installed on the rotor shaft to measure the induced voltage due to a fault in two windings. Analysis of the induced voltage was introduced as a new method to detect the BDB fault. However, the installation of a new slip ring and rewinding the rotor poles based on their polarities is not possible in the power plant generators.

Damper bar current monitoring is proposed in [7] to diagnose the BDB fault. However, the current spectrum of the FFT analysis shows that the amplitude of the side-bands does not follow a consistent trend by increasing the number of BDB fault. Also, temperature rise analysis of SPSG under BDB fault shows that this kind of fault does not change the temperature of the machine in the steady-state adequately.

This paper proposes a novel approach to detect BDB faults in SPSG during start-up time. The start-up procedure in this method first makes the machine to rotate at nominal speed and then subsequently increase the excitation current of the rotor field winding as a ramp function in a few seconds. This paper is organized as follows: Section 2 deals with finite element modeling of the SPSG in healthy and faulty cases. Section 3 provides a theoretical analysis of the pulsation magnetic field in the damper winding and the induced electromotive force in the rotor winding under BDB fault. In section 4, the Time Series Data Mining (TSDM) method is applied to discover if induced voltages in the rotor winding due to BDB can be used to detect the fault. In addition, the effect on the nominated pattern from numbers and location of BDBs faults are studied.

II. MODELING OF SPSG WITH BDB USING FEM

A two dimensional (2-D) scheme of a simulated SPSG using finite element method (FEM) is displayed in Fig. 1. Complete geometrical and physical details of simulated SPSG like stator slots, rotor pole saliency, damper bars are taken into account. Non-linear characteristics of the laminated magnetic core, eddy effects are considered in order to simulate an SPSG in healthy and under BDB fault condition. In this simulation, the SPSG is analyzed under synchronous speed, and with rotor field current increased from zero up to its nominal value. A transient analysis during the machines voltage build-up

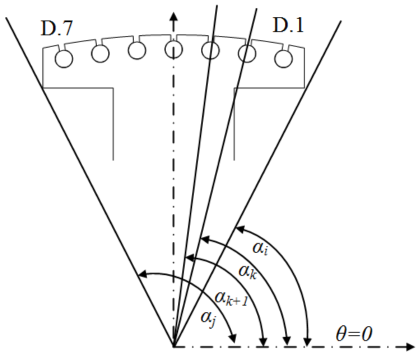

Fig. 2. Rotor pole and location of damper bars of SPSG

was performed to simulate this SPSG. In this FEM model, the motion equation is taken into account to include the mechanical forces coupled with magnetic forces, and the electrical equation to describe the rotor field supply.

Furthermore, saturation, stator and rotor slot design have considerable impact on fault signatures that should be considered in FEM modeling. Time and spatial harmonics due to the machine winding configuration and the power supply play a crucial role in the fault detection procedure. The direct current fed into the rotor field winding by power electronics can cause special time-harmonics in the air gap magnetic field. In addition, stator fractional slot windings can also have noticeable side effects on the flux density and the consequent stator terminal voltage and the load current.

In this model, an SPSG with a rated power of 100 kVA with a stator and rotor lamination consisting of the M-400 material is simulated. Specification of proposed SPSG are shown in Table I. The simulated SPSG model has two layers of the fractional slot stator winding, and a rotor field winding fed by an ideal direct current supply. The BDB during start-up of the SPSG is modeled using FEM. Fig. 2 shows the distributed location of the damper bars in the SPSG. It is assumed that in faulty case, a damper bar is completely broken and the corresponding current is zero.

III. Theoretical Analysis of BDB Fault

A. The Pulsation Magnetic Field due to faulty Damper Bars

The magnetic field in the air gap of the SPSG consists of the field from both stator and rotor in addition to the pulsation flux density from the damper winding. The flux density in the air gap during start-up only includes rotor and damper bars flux density. One of the well known and practical methods of fault diagnosis focus on air gap magnetic flux density monitoring [8]. In order to acquire this signal, hall effect sensors or search coils mounted in stator tooth or slots should be utilized. In transient operations of the synchronous machine, time harmonics in addition to spatial harmonics induce voltages in the rotor damper bars. The damper bars are short-circuited on both ends of the rotor poles by end rings. Consequently, current may pass through the damper bars, which in turn create a magnetic field in the air gap. The amplitude of this magnetic field varies significantly from transient to steady-state operation.

In order to monitor the pulsation magnetic field during machine start-up analytically, the magneto-motive force (MMF) of the damper bars can be calculated as described below [9]:

$$MMF_p(\alpha,t) = \sum_j \sum_\zeta \frac{1}{\zeta}\Big(\frac{2\sin\zeta p(\alpha_{k+1}-\alpha_k)}{\zeta p \pi} \cos\zeta(p - \frac{p(\alpha_{k+1}-\alpha_k)}{2} - \omega t)\Big) I_j \quad (2)$$

where p is the number of pole pairs, α is the angle of damper bar to the reference point in the 2-D plane in radians (Fig. 3), I_j is damper bar current, ω is angular velocity, ζ is the spatial harmonic number since the harmonics of the winding function are expressed by $\zeta = 1 \pm 6n$ where n is an integer.

The pulsation flux density of damper bars (B_p), with respect to the produced magneto-motive force of the damper loop in the active length of machine pole (l), is given by the equation below:

$$B_p = \frac{2\mu_0}{\pi l p} \sum_j \sum_\zeta \frac{1}{\zeta}\Big(\sin\zeta(p + p\alpha_k - \omega t) + \sin\zeta(-p + p\alpha_{k+1} + \omega t)\Big) I_j \quad (3)$$

In regular operation of the SPSG, the air gap magnetic field from the rotor field and the damper bars are symmetrical. According to Eq. 3, the current of the faulty bar passes through adjacent bars, which increase the current density of the loop and causes local saturation. An unsymmetrical current distribution in the SPSG rotor bars results in an unbalanced magnetic field in the air gap.

B. Induced Voltage in the Field Winding due to BDB Fault

An unbalanced magnetic field in the air gap due to a BDB fault induces a voltage in the rotor field winding. The total flux due to this distributed air-gap flux density that interlink poles and damper bars are given as:

$$\phi = \int_{\alpha_i}^{\alpha_j} B_p 2\pi r_r l d\alpha \quad (4)$$

since α_i and α_j are positions of the rotor pole that flux linkages pass through, r_r is the outer radius of the rotor. Based on Faraday's law, induced voltage in the rotor field winding is as follows:

$$e = \frac{2\mu_0 N\omega}{\pi p^2}\Big\{\sum_j \sum_\zeta \frac{1}{\zeta^2}\Big(\sin\zeta(p + p\alpha_k - \omega t) + \sin\zeta(-p + p\alpha_{k+1} + \omega t)\Big) I_j\Big\}_{\alpha_i}^{\alpha_j} \quad (5)$$

where N is the number of turns in the rotor winding. Fig. 3 shows the induced voltage in the field winding of the SPSG in healthy and faulty case. The induced voltage in the

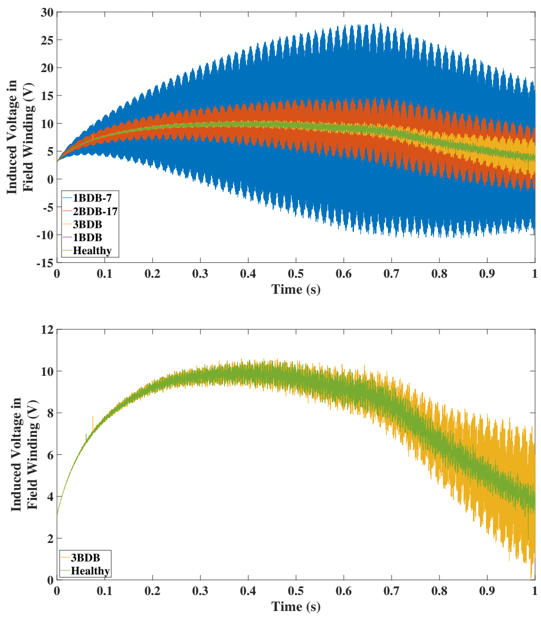

Fig. 3. Induced voltage in the rotor field winding of a SPSG in the healthy, and faulty cases for different number of BDBs.

healthy case is due to the rotor and stator slot harmonics and inherent asymmetry of the machine. A BDB fault increases the pulsation magnetic field which distorts the air gap magnetic field, and consequently increased the amplitude of the induced voltage in the rotor field winding.

The amplitude of the induced voltage in the rotor field winding of the SPSG is directly related to location and number of BDB in the rotor pole. The current amplitude in the middle bars is smaller than the adjacent bars. Since the reluctance of the path that linkage flux pass through middle bars to reach the stator core is smaller than other bars at the edge of the rotor pole. Consequently, the amplitude of the induced voltage in the excitation winding in a case of BDB at the middle of the rotor pole should be less than the rotor pole edge. The amplitude of the induced voltage in a case of three BDB at the middle of the pole is less that one BDB at the edge of the rotor pole as seen in Fig. 3.

IV. The Feature Extraction

Feature extraction is an essential part of the fault detection procedure of electrical machines. An appropriate index must be used to examine the most influenced signal of the SPSG under BDB fault. Sensitivity of obtained signal by FE simulation to BDB fault are examined, and the induced voltage in the rotor field winding is chosen. Since its fault-sensitivity in comparison to other signal is high. On the other hand, the air gap magnetic field of the machine is perhaps the most reliable signal that could be used for various fault detection objective. However, fault detection based on air-gap flux density is an invasive method, requiring the installation of a sensor inside the machine, which is rarely possible. A signal processing tool is also of interest for fault detection of electrical machines. Acquired signals during the transient periods are non-stationary, so most of signal processing tools like FFT is not applicable.

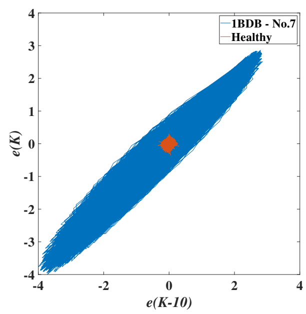

Fig. 4. Phase space of the healthy and one broken damper bar at the edge of SPSG rotor pole.

The Radius of Gyration (RG) could be used as a proper index to scrutinize the trend of BDB fault in SPSG. The RG has a specific value for any number of broken damper bars. RG is based on the time series data mining (TSDM) approach. TSDM is applied to the induced voltage in the rotor field winding in order to detect a hidden pattern due to BDB fault in SPSG during the transient condition.

A. Time Series Data Mining Method

TSDM is a nonlinear signal processing approach which is found on discrete stochastic models of reconstructed phase space based on dynamical system theory [10]. It is proved that a metrically equivalent state space can be regenerated by a single sampled state variable. In other words, dynamical invariants are also preserved in reconstructed state space. The induced voltage in the rotor field winding in two states of healthy and faulty cases is considered as a state variable in order to recover the state space of SPSG. In other words, the acquired signal could reproduce a topologically equivalent state-space similar to original systems of an SPSG, in healthy or faulty cases.

Two methods can be used to reconstruct the state space, which is time-delay embedding and derivative embedding, respectively. Derivative embedding is not practical methods for experimental results since such results have higher-order derivatives that are sensitive to noise. Therefore, time delay embedding that transform scalar points into a vector form, in order to find the invariant of the dynamical systems, is chosen [11], [12]. Assuming that time series of the induced voltage in the field winding is given as follows:

$$e = \{e(j) - e(j-1), j = 2, 3, ..., K\} \tag{6}$$

since j is time index and K is the number of the sampled signal. A reconstructed state space which is also called phase space for j equal to 10 is shown for a healthy and a faulty SPSG in Fig. 4. The RG is used to quantify any changes in the area of the generated mass by TSDM to distinguish between

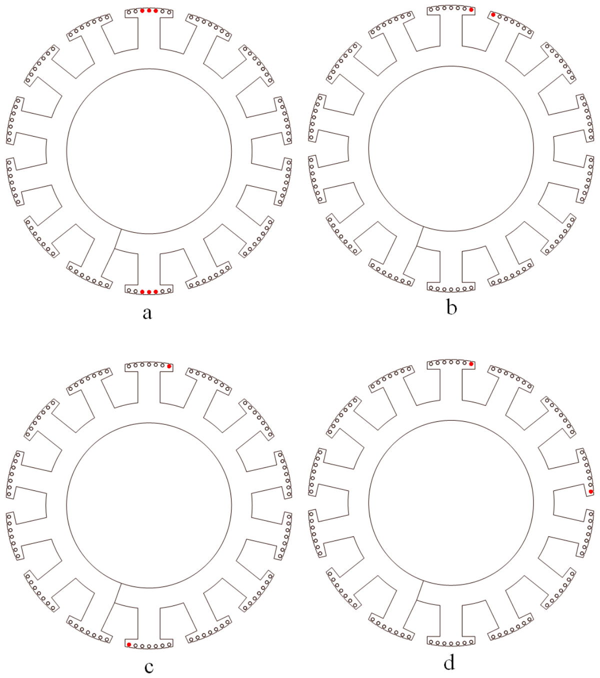

Fig. 5. Location of broken damper bars of the SPSG, (a) six BDBs in each opposite poles, (b) two BDBs in the edge of two adjacent poles, (c) two BDBs in the edge of two opposite poles, (d) two BDBs at two-pole pitch distance.

the healthy and the faulty condition, which is presented below [13]:

$$(RG)^2 = \frac{\sum_{j=1+l}^{K} \left((e(j) - \mu_0)^2 + (e(j-l) - \mu_l)^2 \right)}{K - l} \quad (7)$$

where l is time lag of the phase space, μ_0 and μ_l are centers of gyration for their respective dimension.

The amplitude of the RG is increased upon the BDB fault occurrence. An amplitude of the RG existed even in the healthy case since the machine has some degree of inherent asymmetry. Fig. 4 shows the phase space of the healthy and faulty SPSG with one BDB. According to Fig. 4, a BDB fault increases the radius of the mass, since its radius in the healthy case is 0.1119 and increases to 2.4307 in a case of one broken damper bar. The amplitude of the RG does not show considerable sensitivity when the damper bar at the middle of the rotor pole (DB-4) is broken since the lowest current density is passing through that bar.

Furthermore, the magnitude of the RG in a case with three BDBs at the middle of the pole is less than one BDB at the edge. This because their currents are low. However, the RG increment due to a fault depends on the location and number of BDB. For instance, the most significant amount of current passing through the bars, at the edge of the rotor poles, consequently, its variation with respect to the other bars should be more noticeable. The location of the BDB is a critical factor that could modify the amplitude of the RG. In a case where the BDB fault happens at two edge bars of the same pole, its RG value is less than having one BDB at the edge. The pulsation magnetic field due to two BDBs at the edge of the pole is twice the one BDB. However, the symmetry of the faults mostly canceled out the pulsation magnetic fields. However, they do not entirely wipe out their effects, so there is still asymmetry in air gap magnetic field that gives rise to the RG index. The worst-case that increases the amplitude of the RG considerably is two adjacent BDB at same pole. In this case, the current of the two BDBs passes through the third one that causes local saturation. As a result, the pulsating magnetic field, local saturation, and lack of magnetic field due to BDBs leads to the intense unbalanced magnetic field which induced a large voltage in the rotor field winding.

TABLE II
RADIUS OF GYRATION IN HEALTHY AND FAULTY SPSG FOR DIFFERENT NUMBER AND LOCATION OF BDBS

Cases	***RG***	***Cases***	***RG***
Healthy	0.1119	Healthy	0.1119
1BDB-No. 4	0.1121	3BDB (middle bars of 1 pole)	0.3424
1BDB-No. 6	0.4091	6BDB in two poles (case a)	0.6685
1BDB-No. 7	2.4307	2BDB-No. 7, 1 (case b)	2.3577
2BDB-No. 6, 7	4.0743	2BDB-No. 1, 7 (case c)	4.8344
2BDB-No. 1, 7	1.0442	2BDB-No. 1, 1 (case d)	1.3047

B. Effects of Broken Damper Bar Location on the Proposed Index

The magnitude of RG depends on the asymmetry level of the air gap magnetic field caused by the BDB fault location. Fig. 5 shows the locations of BDB faults in different rotor poles. The third and fourth columns of Tab. II shows the variation of RG index with respect to the location of the BDB fault in different poles. In case (a), the amplitude of the RG in comparison to three BDB in one pole is increased two times. However, due to low current density at the middle bars, it is anticipated that its value should not be increased according to the number of BDBs. Although it is expected to have a higher degree of RG in case (b), which has two BDBs at the two edges of adjacent rotor pole, its amplitude does not increase in comparison to one BDB at the edge of one pole. Since the flux density level changes over the circumference of one of the poles (north or south). In case (c), both of the rotor poles have the same flux density polarity, which in turn increases the amplitude of the RG by a factor two of a BDB at the edge of the pole. In case (d), the amplitude does not increase but partly decreases, which could be explained based on the case (b).

V. CONCLUSION

This paper deals with the detailed modeling, analytical study, and condition monitoring of SPSG under BDB faults. The analytical approach proved that damper bars induce a pulsation magnetic field due to the variation of damper bar currents as a result of the BDB fault that can distort the air gap flux density. This flux distortion induces an electromotive force in the rotor field winding that had an extreme sensitivity to BDB faults compared to the non-invasive methods. The time-series data mining method was applied to the induced voltage at the rotor field terminal in order to extract the precise feature to diagnose BDB fault. It was shown that this index has a high degree of sensitivity to the BDB faults. In addition, the effects of the number of bars and its location on RG was studied. It was shown that the amplitude of RG was increased by increasing the number of BDBs. Besides, the magnitude of RG could be increased if BDBs were located in the poles with the same polarity.

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