Adaptive Hysteresis Current Control For Improved EMI Performance in Fast Switching Motor Drives

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***Abstract*—Electromagnetic interference (EMI) in pulse width modulated converters is exacerbated through carrier based modulation techniques that are associated with sharp spectral peaks around multiples of the switching frequency. As a mitigation measure, spread spectrum techniques are used, that distribute the carrier spectral energy over a certain frequency range to attenuate the EMI spectrum. This paper presents an alternative implementation of spread spectrum modulation through adaptive hysteresis bands, that regulate the moving average of switching frequency in a current controlled permanent magnet synchronous motor drive. Simulation results are presented through a comparison of input EMI and common mode voltage spectra for different modulation techniques. The proposed method demonstrates notable attenuation of spectral peaks when compared to carrier based modulation, while simultaneously overcoming large switching frequency deviations that are otherwise prevalent in classical hysteresis current control.**

***Topic*—Electric Drives** (*EMI reduction, adaptive control, spread spectrum techniques*)

Nomenclature

EMI	Electro-magnetic interference.
PMSD	Permanent magnet synchronous motor drive.
DEMI	Differential mode electro-magnetic interference.
CMV	Common-mode voltage.
LISN	Line impedance stabilization network.
HCC	Hysteresis current control.
f_{sw}^{*}	Reference switching frequency.
$\tilde{f}_{sw(x)}$	Moving average of switching frequency.
Δf_{sw}	Switching frequency deviation from reference.
$H_{(x)}$	Hysteresis band width in phase 'x'.
V_{dc}	Input DC voltage to the drive.
$E_{(x)}$	Back emf in phase 'x'.

I. Introduction

The last decade has witnessed significant improvement in power density of motor drives due to rapid penetration of wide band gap devices in converter design. In spite of their advantages, fast switching converters are often under-exploited due to concerns of electro-magnetic interference (EMI) [1]. Rapid switching transients are particularly undesirable in motor drive applications, where they are known to cause bearing currents, overheating and motor lifetime reduction [2], [3]. EMI emissions increase with device switching speeds as well as switching frequency, and mitigation is generally considered as a design problem where emphasis is laid on prototyping, layout and filter design [4], [5]. However, the role of modulation techniques in EMI performance cannot be undermined, especially in terms of the flexibility in control. Carrier based modulation techniques and other fixed period pulse width modulation (PWM) techniques produce high magnitude spectral peaks at multiples of the switching frequency, and if the switching frequency is high, these peaks can penetrate well into the EMI spectrum range (150 kHz- 30MHz). Spread spectrum techniques such as carrier frequency modulation have been previously proposed to reduce EMI emissions in power converters by attenuating periodic spectral peaks that are otherwise generated in fixed switching frequency modulation [6]–[8]. Hysteresis current control (HCC) is an innately spread spectrum switching technique for power converters, where currents of interest are restricted within a hysteresis band through appropriately timed switching decisions. The technique is quite popular for its ease in implementation and inherent over-current protection. Furthermore, HCC can potentially be used for EMI mitigation due to its natural tendency to spread the spectrum. However, the technique yields large fluctuations in switching frequency that often make filter design quite cumbersome, due to random harmonic distribution in the range of switching frequency variations.

This paper proposes an adaptive hysteresis current control technique for a permanent magnet synchronous motor drive (PMSMD), where the width of hysteresis band is varied in real time to regulate the moving average of switching frequency. The gating pulses to each leg of the converter are used as feedback in modulating the width of the hysteresis band, which in turn controls the switching frequency deviations. This helps curb the rapid cycling of switching frequency, thereby improving the harmonic spectrum around the low frequency range (i.e close to the switching frequency). At the same time, the algorithm does not maintain a constant switching frequency (f_{sw}) but a constant moving average of f_{sw}. This helps spread the spectrum to attenuate the spectral peaks of EMI in the high frequency range (i.e around higher order multiples of the switching frequency).

Performance of the proposed technique is demonstrated through a comparison of input EMI and motor common mode voltage for three modulation approaches, viz. carrier based modulation, classical hysteresis control and the proposed adaptive hysteresis control. Through simulation analysis, it is validated that the proposed technique attenuates spectral peaks of higher order EMI that are otherwise dominant in carrier based modulation, without generating wide variations in switching frequency unlike classical hysteresis control.

II. Adaptive Hysteresis Current Control

Hysteresis current control (HCC) with fixed hysteresis band is widespread in motor drive applications due to its simple implementation and fast dynamic response. In classical HCC based permanent magnet synchronous motor drive (PMSMD), switching frequency (f_{sw}) varies as a function of DC link voltage, motor back emf, stator inductance, rate of change of reference motor currents and width of the hysteresis band [9]. Assuming that f_{sw} is much larger than the fundamental stator frequency, the rate of change of reference currents may be neglected and f_{sw} can be represented as,

$$f_{sw} \propto \frac{V_{dc}^2 - E^2}{H} \tag{1}$$

where V_{dc} is the inverter input DC voltage, E is the motor back emf and H is the width of the hysteresis band.

The primary drawback of classical HCC is large variation in switching frequency (Δf_{sw}) that may necessitate an over-sized input filter to be designed in accordance with the lowest frequency of switching. Alternatively, adaptive or time-varying hysteresis band (H) may be used instead of a fixed band, that helps achieve nearly constant switching frequency [9], [10].

In terms of EMI performance in fast switching wide band gap converter fed drives, constant switching frequency operation is undesirable due to high amplitude spectral peaks observed at multiples of the switching frequency, which can penetrate well into the higher end of the spectrum. Presence of spectral peaks in the motor common mode voltage especially at high frequency (in the range of MHz) can generate significant conducted common mode EMI besides affecting the motor lifetime [3]. In fact, EMI concerns often limit the switching frequency in carrier based control, hence impeding the optimum use of WBG devices in power converters. Literature reports the use of spread spectrum techniques such as chaotic PWM and carrier frequency modulation to attenuate spectral peaks of EMI [6]–[8], [11]. These techniques tend to spread out the carrier harmonic energy over a frequency range, hence attenuating the localized spectral peaks that are otherwise observed with constant switching frequency. In spite of the fact that HCC is an inherently spread spectrum technique, its use for EMI mitigation has not been reported so far, even though spread spectrum techniques are favourable for electromagnetic compatibility.

This paper proposes a novel adaptive HCC technique to regulate the moving average of switching frequency, using instantaneous gating pulse feedback to vary the hysteresis band (H). This ensures that switching frequency deviations (Δf_{sw}) are just enough to spread the spectrum and attenuate spectral peaks in the high frequency region (unlike carrier based modulation) but not too large to amplify the spectrum in the range of deviations (unlike classical HCC). For implementation of the proposed technique, the moving average of switching frequency is calculated from real-time gating signals of the top (or bottom) device in each leg. It is then compared with a reference switching frequency, and the negated integrated error is used to modulate the width of the hysteresis band. Since the switching frequency is inversely proportional to the width of the hysteresis band, the error in switching frequency is negated. The band shape is also tuned using real-time calculations of DC link voltage and motor back-emf in accordance with (1). The adaptive hysteresis band for each phase ($x = a, b, c$), is therefore, given as,

$$H_{(x)} = -\frac{k_i}{s}(f_{sw}^* - \widetilde{f}_{sw(x)}) \times (V_{dc}^2 - {E_{(x)}}^2) \tag{2}$$

where, k_i is the integrator gain which is chosen heuristically, $\widetilde{f}_{sw}$ is the moving average of real-time switching frequency and f_{sw}^* is the reference switching frequency. From (2), the hysteresis band width is evaluated independently for each phase, ($x = a, b, c$) using real-time moving average of switching frequency of each leg and back-emf approximations of the corresponding phase. For each phase, the back-emf is approximated to be in phase with the stator current and is given as,

$$\begin{aligned} E_{(a)} &= \omega_e \phi \cos(\omega_e t) \\ E_{(b)} &= \omega_e \phi \cos(\omega_e t - (2\pi/3)) \\ E_{(c)} &= \omega_e \phi \cos(\omega_e t + (2\pi/3)) \end{aligned} \tag{3}$$

where, ω_e is the electrical frequency in rad/s and ϕ is peak flux linkage established by the rotor magnets.

For minimal processor burden, moving average, $\widetilde{f_{sw}}$ used in the control, is spanned over two data points only, i.e the current and previous controller samples of gating pulse. Since the sampling period of the controller is much smaller than the average switching period, the two-sample moving average of switching frequency, $\widetilde{f_{sw}}$ is a highly discrete signal, thus necessitating an integrator in the control loop. For observing the switching frequency of the converter, a larger window of a few thousand samples may be used. The effect of varying window sizes of the moving average controller in EMI suppression can also be evaluated. However, for simplicity and reduced processor burden, this paper implements two-sample moving average only.

III. EMI Performance Analysis

To demonstrate the performance of the proposed algorithm, simulation analysis is presented for an eight pole, three-phase PMSMD, which is controlled through space vector modulation (carrier based implementation), classical HCC and the proposed adaptive HCC technique. A comparison of modulation techniques is drawn through spectra of motor common mode voltage (CMV) and DC side differential mode EMI (DEMI). For EMI measurements on the input side, a line impedance stabilization network (LISN) is used, that provides a shunt path to input differential noise for spectral measurement. Fig.1 shows the LISN, input filter and the converter fed PMSMD. Various system and simulation parameters are enlisted in Table I. For a fair comparison, the same input filter (with a cut-off of about 100 kHz) is used for analysis with all modulation techniques. All results are demonstrated at a motor speed of 2000 rpm with typical vector control.

Figs.2 (a) & (b) show a comparison of classical HCC and adaptive HCC for parameters such as moving average of switching frequency $\widetilde{f_{sw}}$, stator currents (i_{abc}) waveform, and width of the hysteresis band (H_a) in phase 'a'. Quite evidently, there is wide variation ($> 100kHz$) in switching frequency for the fixed band classical HCC technique, which is overcome through adaptive HCC, wherein the hysteresis band is varied in real-time to regulate the moving average of switching frequency.

In fast switching motor drives, high frequency common mode voltage (CMV) between the stator neutral and external ground often leads to bearing currents, overheating and common mode EMI. Mitigation measures usually include output EMI or dv/dt filters which add volume to the drive, hindering high power density design. Alternatively, high frequency CMV peaks can be strategically attenuated through control. Fig.3 shows the spectrum of CMV for carrier based control, classical HCC and the proposed adaptive HCC technique. With carrier modulation, high amplitude spectral peaks are observed in the high frequency region, where layout/parasitic/cable capacitances have a more pronounced role in drawing common mode currents. Although classical HCC demonstrates spectral peak attenuation in the high frequency region ($>$ 4 MHz), it is associated with overall raised EMI below 4 MHz. This is because of the rapid cycling of switching frequency from 50 to 200 KHz. The adaptive HCC technique with minimized switching frequency variations (constant moving average), generates a spectrum similar to carrier control in the low frequency region, while imitating classical HCC in the high frequency region, thus embedding the best features of both techniques.

Fig.4 shows the LISN measurements of input differential mode EMI (DEMI) for carrier control (Fig.4(a)), classical HCC (Fig.4(b)) and adaptive HCC (Fig.4(c)). Due to rapid frequency cycling in classical HCC, significant noise levels are observed in the range of frequency deviations, unlike carrier based control which operates at constant switching frequency or adaptive HCC where frequency variations, Δf_{sw} are restricted. This can be further observed in Fig.5 which shows the spectrum of input DEMI for the three control techniques. A zoom-in close to the switching frequency range shows overall higher magnitude of noise levels in classical HCC than carrier control or adaptive HCC. Unlike carrier control, adaptive HCC also showcases diminished spectral peaks in the higher end of the spectrum.

Finally, it is observed that the proposed adaptive HCC technique not only enhances the EMI performance of the drive, but it also improves the motor current quality when compared to the classical HCC technique. This is observed through a comparison of harmonic spectra of motor currents as shown in Fig.6. A more pronounced effect on harmonic performance will be observed for lower switching frequencies. However, since the scope of this work is to evaluate EMI performance, therefore, high switching frequency close to EMI relevant range is chosen.

IV. Conclusion

An adaptive hysteresis current control technique is presented in this paper, that facilitates rapid switching in power dense motor drive applications through EMI mitigation. The proposed technique is inspired from spread spectrum modulation for EMI reduction, such that switching frequency deviation is contained within a small range, to spread the spectrum and, hence, reduce spectral

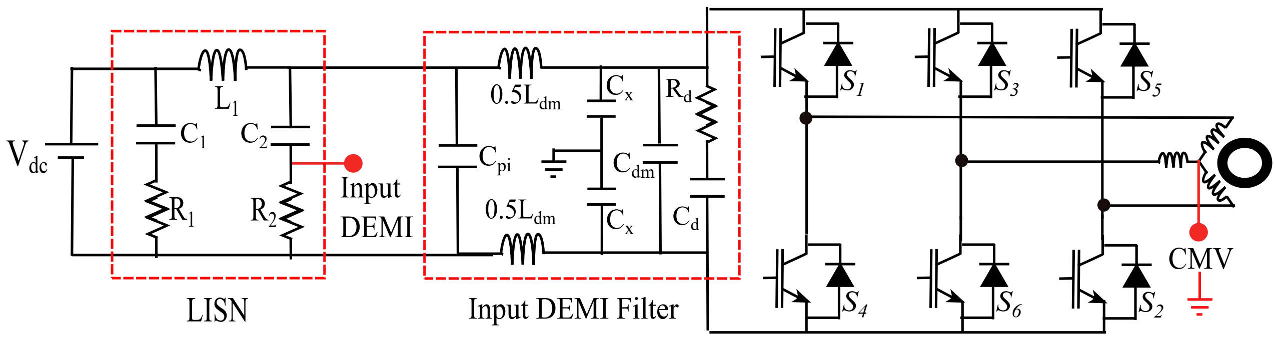

Fig. 1: Three-phase PMSMD test system with DC LISN and input differential EMI filter

Table I: System Parameters

LISN		Input DEMI Filter		System Parameters	
L_1	$50\mu H$	L_{dm}	$0.8\mu H$	Input Voltage, V_{dc}	$48\ V$
C_1	$8\mu F$	C_x	$0.1\mu F$	f_{sw} (carrier control/adaptive HCC)	$100\ KHz$
C_2	$0.25\mu F$	C_{pi}	$0.5\mu F$	Sample Time	$50\ ns$
R_1	5Ω	C_{dm}	$5\mu F$	Stator Resistance	$0.4\ \Omega$
R_2	1000Ω	C_d	$25\mu F$	Stator Inductance	$466\ \mu H$
		R_d	0.4Ω	Motor Voltage Constant	$14.4\ V_{peak}/krpm$

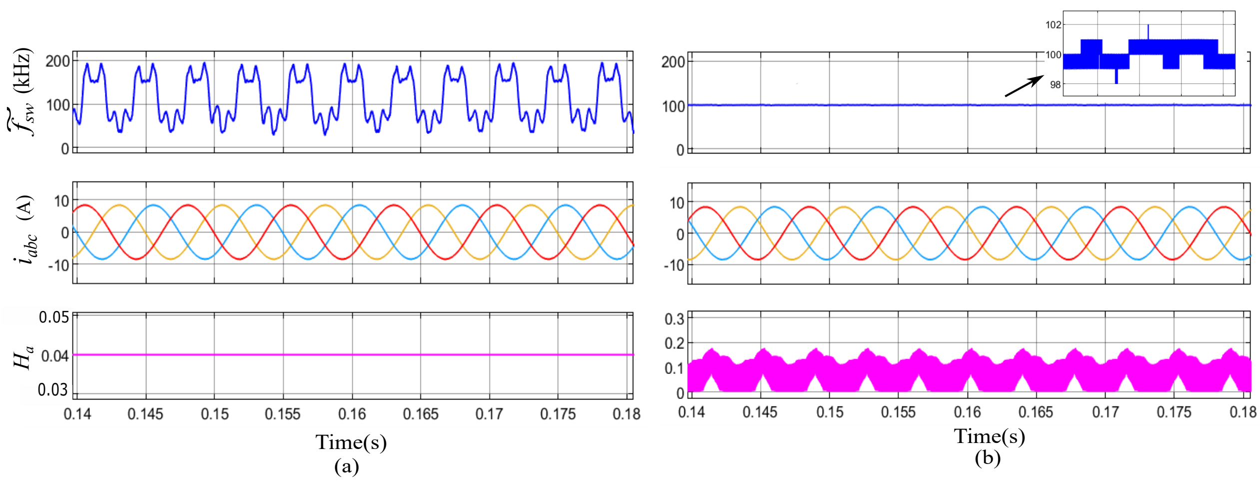

Fig. 2: Performance comparison (a) Classical HCC (b) Proposed adaptive HCC

peaks of EMI. This is achieved by real-time variation of hysteresis band to control the moving average of switching frequency. Besides being superior to classical HCC due to limited Δf_{sw}, the proposed method exhibits spectral peak attenuation in the high frequency range as an advantage over carrier based control. The performance of the proposed technique is validated via simulation based comparison with other control techniques, in terms of the spectra of common mode voltage and input differential mode noise in a permanent magnet synchronous motor drive application.

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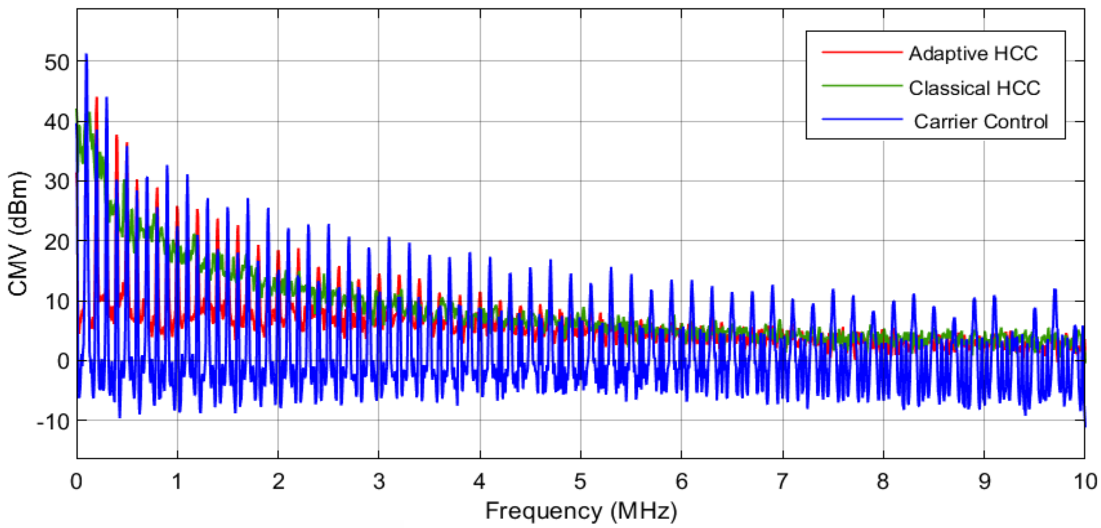

Fig. 3: Spectrum of common mode voltage for carrier control, classical HCC and adaptive HCC technique

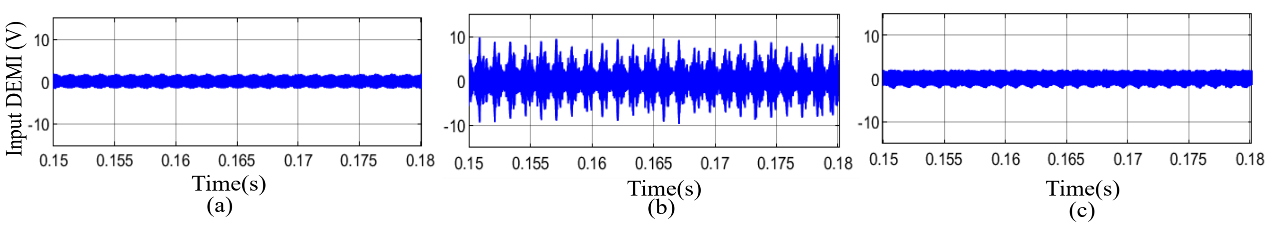

Fig. 4: LISN measurement of input side differential mode noise for (a) carrier control (b) classical HCC and; (c) adaptive HCC

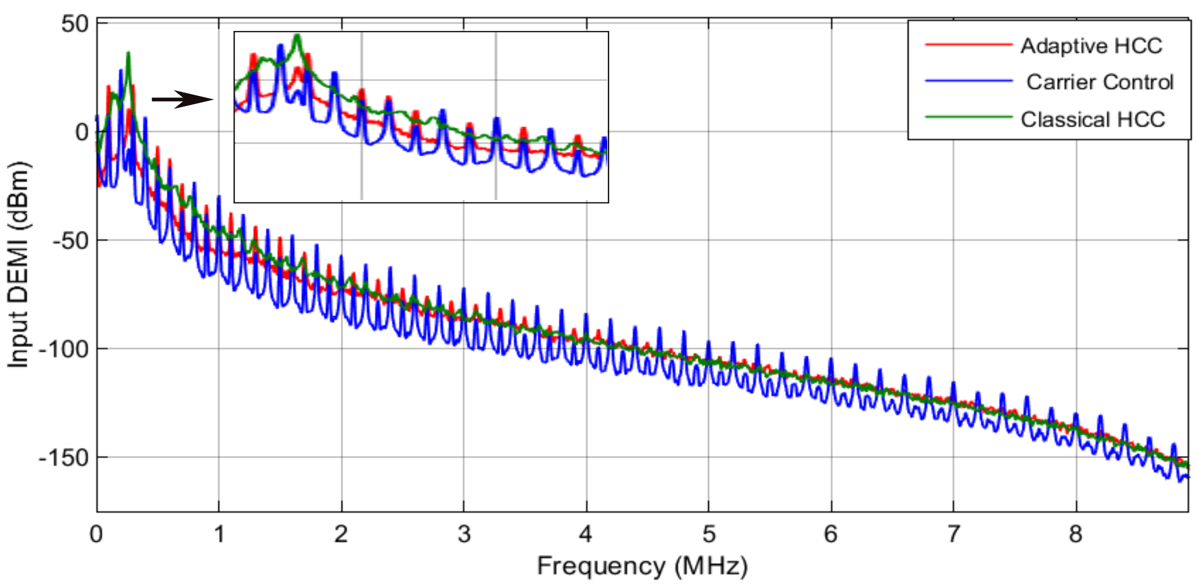

Fig. 5: Spectrum of input side differential mode noise for carrier control, classical HCC and adaptive HCC technique

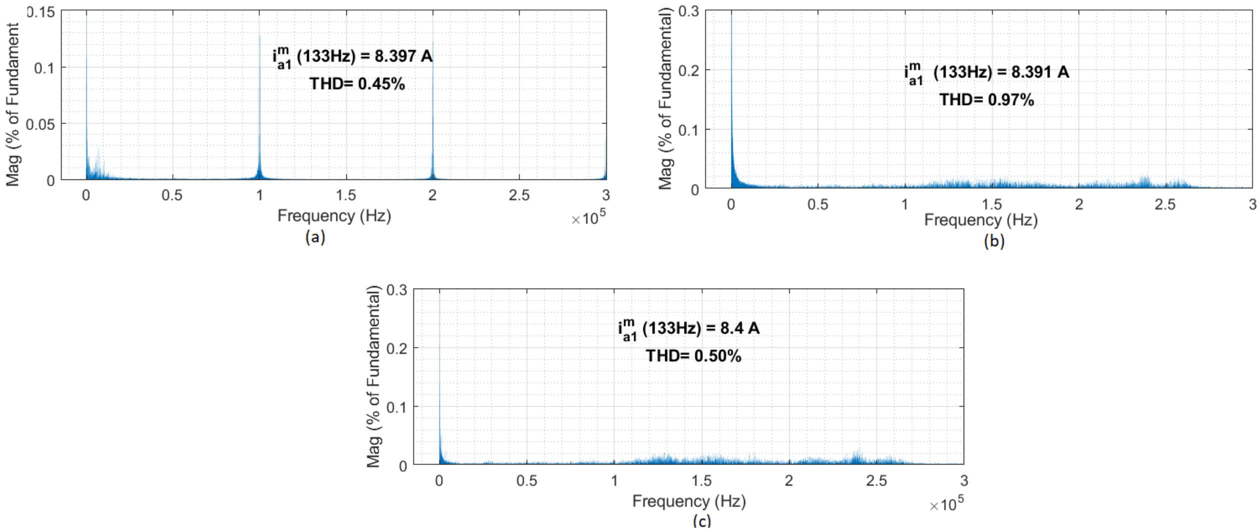

Fig. 6: Harmonic spectrum of motor current for (a) carrier control (b) classical HCC and; (c) adaptive HCC

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