Efficiency-Oriented Design and Control of Multilevel Power Converter–Fed Electrical Machines for Grid-Connected and Industrial Applications

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Article Info	ABSTRACT
	The trend toward using grid-connected and industrialized electric drive packages requires better efficiency, more valuable power quality, and full adherence to grid standards. The natural benefits of multilevel power converter fed electrical machines include: less harmonic distortion, less voltage stress and more power scalability. Nonetheless, traditional methods of control are mainly aimed at dynamic executing and do not take into account the integrated loss optimization and therefore, have low efficiency in different operating environments. With a proposal based on efficiency-oriented design and control framework of multilevel converter fed electrical machines is put in this paper which explicitly considers converter as well as machine losses. Loss modelling approach is developed in a comprehensive manner with semiconductor conduction and switching losses as well as machine copper, core and mechanical losses. According to this model, the loss-aware control strategy is developed that dynamically optimises the existing references without affecting the accuracy of torque and grid power quality. Experiments of simulation show that overall efficiency and total losses and grid current harmonic distortion were reduced in comparisons to more than traditional control schemes and the schemes are therefore feasible in the field of industrial automation and grid-connected drive applications.

1. INTRODUCTION

The high growth of grid-connected and industrial electric drive systems has contributed a major challenge on the high efficiency as demand and the best quality of the power and the increased operational reliability in view of high efficiency [1], [7]. Multi-level power converters have achieved popularity in the use of electrical machines that feed into medium and high power applications, including (but not limited to) integration of renewable energy into power systems, industrial automation, traction, and heavy motor drives [1], [5], [9]. Multilevel converter topologies have less stress on power devices due to reduced voltages, less harmonic distortion, better electromagnetic compatibility, and better scalability, and are therefore especially appealing to modern grid-interfaced and industrial applications [1], [7], [10], [12]. Although such benefits come with it, the general performance of multilevel converter fed electric machines is heavily determined by the control strategy applied [2], [4]. Innovative control strategies like proportional-integral (PI)-based field-oriented control (FOC) is common because it is straightforward and can perform well in nominal operating conditions [2], [4]. Nevertheless, each of the methods is usually aimed at accurate control of torque and speed without much attention to efficiency of the overall system [3], [8]. This leads to converter switching losses, machine copper losses and core losses being treated or neglected in the controller design [3], [8], and [9]. This does not provide coordinated loss awareness in perilous loads, grid disturbances, and partial-load setting, which results in high energy consumption, lowered efficiency, and the optimum performance of power quality [3], [6], [10]. In a bid to overcome such issues, there has been an increasing necessity to develop control structures that explicitly implement both converter as well as machine loss properties in the control design [8], [9], [11]. A converter-and-machine integrated efficiency-oriented strategy makes it possible to dynamically optimise the operating points, develop a better loss distribution, and achieve better grid power quality requirements [6], [9], [10], and [11].

These strategies are specifically important where energy efficiency, thermal constraints, and long term operation costs are crucial performance measures [1], [5], [9].

The principal conclusions of the present paper are summarised as follows:

- Efficiency-based and systematic, unified modelling of the multilevel power converter and electrical machine, accounting transpicuous converter and machine loss elements.

- Many other strategies exist which may be explored to achieve a loss-aware control strategy as suggested by the author dynamically optimising current references in order to reduce the total system losses without affecting the torque accuracy or grid power quality.

- Comparative performance analysis showing the improvement of efficiency, reduction of losses and harmonious reduction under the representative grid connected and industrial operating conditions.

2. System Architecture and Modeling

2.1 Multilevel Converter–Fed Machine Drive Configuration

The system in case of study is a grid-connected multilevel power converter supplying an electrical machine by an efficiency based control structure. Inverters Multilevel converter topologies including the neutral-point-clamped (NPC), active neutral-point-clamped (ANPC) and cascaded H-bridge (CHB) inverters are finding extensive application in medium and high-power drive systems because they can produce high-quality voltage waveforms with less device voltage stress and less harmonic distortion. A generic multilevel converter model representation is taken into consideration in this work to make the proposed modelling and control method applicable to a wide range of topologies, regardless of the implementation of a particular topology.

The multilevel converter is connected to the utility on the grid side with the assistance of a passive philtre, which limits switching harmonics and secures that the converter meets the requirements of the quality of grid power. The grid interface allows manipulation of power exchange and at the same time keeps current total harmonic distortion low and power factor has been kept close to unity. At the machine end, converter provides balanced three-phase voltages to the electrical machine with which the torque and speed of the machine can be controlled with precise control considering the varying operating conditions. The electrical machine can be of the type of induction machine or permanent magnet synchronous machine, either of which is common in industrial drive systems and grid-connected drive systems. Fig. 1 displays the overall system architecture which depicts the grid interface, multilevel inverter, electrical machine and efficiency orientated control structure. Such a structure lays the foundation of the dynamic modelling and loss-conscious control strategy that is designed in the following sections.
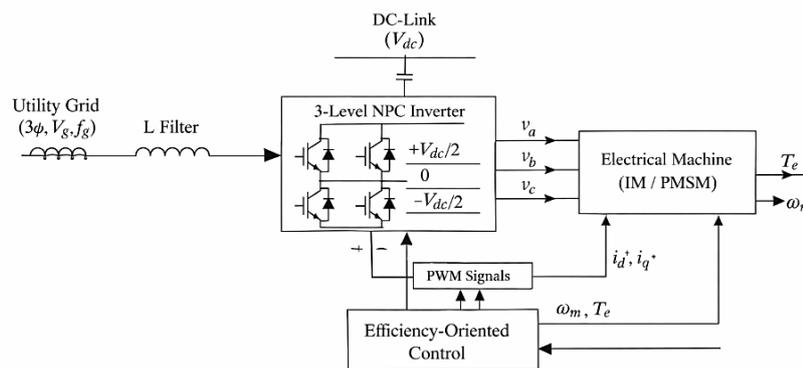
Fig. 1: Overall system architecture of multilevel converter–fed electrical machine drive

2.2 Model of an electrical machine Dynamics

The dynamic behavior of the electrical machine is described in the synchronously rotating dq reference frame, which enables decoupled control of torque and flux components and is widely adopted in high-performance electric drive systems. Generalised to the right parameter definitions, this framework of modelling applies to both the induction machines and permanent magnet synchronous machines. In the synchronous dq reference frame, the stator voltage equations of the electrical machine are expressed as follows:

$$v_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_e \psi_q$$
$$v_q = R_s i_q + \frac{d\psi_q}{dt} - \omega_e \psi_d \qquad (1)$$

Where v_d and v_q are the stator voltage components, i_d and i_q denote the stator current

components, ψ_d and ψ_q and represent the stator flux linkages along the direct and quadrature axes, respectively. The parameter R_s is the stator resistance, ω_e denotes the electrical angular speed of the rotating reference frame. It is based on the above formulation that the further development of the torque modelling and development of more loss-conscious control is provided, which allows efficient control of the machine work in both grid-connected and industrial drive conditions.

2.3 Electromagnetic Torque Expression

The electromagnetic torque developed by the electrical machine can be derived from the interaction between the stator flux linkages and current components in the synchronously rotating dq reference frame. This expression gives a concise and broad expression that can be used in the case of an induction machine, as well as permanent magnet synchronous machine when the parameters are defined appropriately. The electromagnetic torque has been calculated as:

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_d i_q - \psi_Q i_d), \text{_____ (2)}$$

Where T_e denotes the electromagnetic torque, P is the number of machine poles, ψ_d and ψ_q represent the stator flux linkages along the direct and quadrature axes, and i_d and i_q are the corresponding stator current components. The fact that current components that produce flux and current components that produce torque are inherently decoupled is emphasised by equation (2), and is the basis of control strategies that are efficiency-oriented. Through adequate control of the dq-axis currents, one can sustain the electromagnetic torque and keep to a minimum the losses of the entire machine and converter as discussed in the following sections.

3. Efficiency-Oriented Loss Modelling.

3.1 Converter Loss Model

Power losses in converter in multilevel power converter-fed electrical machine drives are a large part of the total system losses, and directly affect the efficiency of the system and thermal performance. Such losses mainly occur in conduction and switching of semiconductors and change with operating conditions, e.g., load current, DC-link voltage and switching frequency. Correct Converter loss modelling is consequently the key to the development of efficiency-focused control strategies. The overall power loss of the multilevel converter can be given as the conduction loss plus switching loss, which is given as the following:

$$P_{conv} = P_{cond} + P_{sw}, \text{_____ (3)}$$

Where P_{conv} denotes the total converter power loss, P_{cond} represents the conduction losses of the semiconductor devices, and P_{sw} accounts for the switching losses associated with turn-on and turn-off transitions. Both of the loss terms are dependent on the level of phase current, device voltage levels that are present under a multilevel operation, and the switching frequency that is applied. The formulation of loss as given is a convenient form of loss realisation model under which converter loss awareness can be expressed in the control design that can be used to dynamically optimise switching behaviour and references in the current optimization that allows ideal overall drive efficiency.

3.2 Machine Loss Model

The electrical machine, as well as converter losses, also causes high electricity machine losses, especially in impulsive load conditions and part load operating conditions. Proper modelling of machine losses is hence critical towards the attainment of integrated efficiency-based control strategy. The leading loss elements in electrical machines are losses in copper wind readings of the stator, labour in magnetic cores and mechanical losses through friction and wind age. The power loss of the machine in total is given as:

$$P_{mach} = P_{cu} + P_{core} + P_{mech}, \text{_____ (4)}$$

where P_{mach} denotes the total machine loss, P_{cu} represents the stator copper losses caused by resistive heating, P_{core} corresponds to magnetic core losses arising from hysteresis and eddy current effects, and P_{mech} accounts for mechanical losses due to bearing friction and air resistance. The operating factors that affect these loss components include the current magnitude, flux level, rotational speed and the load conditions. The addition of the machine loss model alongside the converter loss modelling allows performing an efficient evaluation of the drive system as a whole and the loss-conscious control strategy proposed is based on it.

3.3 Overall Drive Efficiency

The ratio of useful mechanical output power to total input power of a multilevel power converter-fed electrical machine drive becomes the overall efficiency of this device considering the losses in both the converter and electrical machine. A well-defined efficiency formulation is also needed to determine system performance as well as to come up with control measures that would be taken to ensure energy losses given different operating conditions are kept to a minimum. Drive efficiency: The total drive efficiency is given as:

$$\eta = \frac{P_{out}}{P_{out} + P_{conv} + P_{mach}}, \text{_____ (5)}$$

Where η denotes the overall drive efficiency, P_{out} is the mechanical output power delivered by the electrical machine, P_{conv} represents the total power loss in the multilevel converter, and

P_{mach} denotes the total electrical machine loss. Equation (5) offers a single measure of the effect of converter-side and machine-side losses on the behaviour of the system. This formulation is literally utilised in the suggested efficiency-based control model in that the operating conditions are dynamically optimised to ensure no torque accuracy and grid power quality.

4. Suggested Efficiency-based Control Strategy

The proposed control strategy will help increase the total efficiency of the multilevel converter fed electrical machine drive to directly integrate converter and machine losses information into a control loop. This is in contrast to traditional vector control schemes, which insist mostly on tracking torque and speed normal operating conditions and the approach presented in this paper proposes a loss-conscious supervisory layer, which optimises operating points in a dynamic manner without compromising the dynamic performance and quality of grid power. The combination of this framework allows implementing the systematic decrease of the energy losses without jeopardising the stability and responsiveness of the control. The control strategy will aim at fulfilling three major goals. To begin with, it aims at reducing the total system losses that occur due to both multilevel power converter and the electrical machine just as the models of the losses discussed in Section 3.1.The reduction of semiconductor conduction and switching losses in the converter and copper and core losses in the machine are minimised to maximise the drive efficiency. Second, both steady-state and transient operating conditions have been reported to have the appropriate torque and speed tracking performance. The optimization layer of efficiency works in harmony with the inner current control loops and it guarantees that the loss minimization process does not have a negative impact on the dynamic response and stability of the system. Third, to operate on a grid, the control strategy provides the Internet of grid power quality requirements such as low current harmonic distortion and appropriate power factor through coordinated current regulation and PWM-based multilevel modulation.

Fig. 2: Control block diagram of the proposed efficiency-oriented control scheme

In order to achieve these goals, loss-aware reference current generation mechanism is integrated in hierarchical control architecture. Conventional dq-axis current control forms the inner control layer, while a supervisory loss-aware optimization block dynamically adjusts the operating point based on estimated converter and machine losses. The current reference of the main direct axis and the quadrature axis are adapted to achieve a compromise between the generation of the torque and the efficiency maximisation. While the i_q component primarily governs electromagnetic torque generation, the i_d component influences machine flux levels and, consequently, core losses and converter current stress. By jointly optimizing the i_d–i_q current components, the proposed strategy identifies an operating point that minimizes the total system loss defined in (5) while satisfying the required torque demand. Besides the adaptive current reference generation, switching-frequency optimization is also added, which further minimises converter switching losses. Switching frequency is also set based on the load requirements and efficiency and allows an optimal trade-off between the switching losses and harmonic performance. The complete control architecture—comprising the loss-aware optimization block, reference generation, dq-axis current controllers, coordinate transformations, and PWM-based multilevel modulation—is illustrated in Fig. 2. This design allows combining efficiency optimization in a classical, deterministic control system applicable in the grid-connected

and industrial electrical drive applications environmentally.

5. Simulation Experiments and Test Conditions

In order to confirm the succinctness of the suggested efficiency-centred approach to a control strategy, elaborate simulation experiments were conducted in MATLAB/Simulink and PLECS was used to illustrate the power electronic scheme in detail. The simulation model is a multilevel converter fed electrical machine driver that can be run under grid connected and industrial load. Control architecture that is stated in Section 4 and shown in Fig. 2 was completely applied to the simulation environment. As a typical example of a multilevel topology, a three level neutral-point-clamped (NPC) inverter was taken, driven by a regulated DC-link voltage source. Multilevel modulation was done using PWM to better synthesise inverter output voltages, and also allow switching-frequency optimization of losses. The electrical machine was modeled using the synchronous dq-axis equations presented in Section 2, allowing accurate representation of electromagnetic torque production and dynamic behavior.

Variable mechanical loading and grid-interfacing effects were added to simulate operating conditions which are realistic. Under different load tires that varied with the proposed control strategy, the effectiveness of the proposed control strategy in adapting current references as well as loss minimization during partial-load and rated-load operations were considered. Tests were made to determine speed transient behaviour to determine the dynamic performance and tracking performance under the rapid change of reference speed. Also, grid connected operation was investigated in order to cheque the present waveform quality, harmonic distortion and adherence to grid power quality requirements. The most important electrical machine and converter parameters in the simulation study are listed in Table 1.

Table 1. Electrical Machine and Converter Parameters

Parameter	Value
Rated power	5 kW
Rated line voltage	400 V (three-phase)
Rated speed	1500 rpm
DC-link voltage	700 V
Switching frequency	5 kHz
Number of inverter levels	3
Machine type	Induction Machine / PMSM
Grid frequency	50 Hz

Sampling time	50 µs

6. Output and Performance Review

Simulations of the efficiency-oriented control strategy were carried on in details, and compared with the traditional PI-based control scheme of vectors. The test is aimed at enhancing the efficiency, enhancing the quality of power, and reducing the total loss under model operating conditions of multilevel converter from-fed electric machine drives.
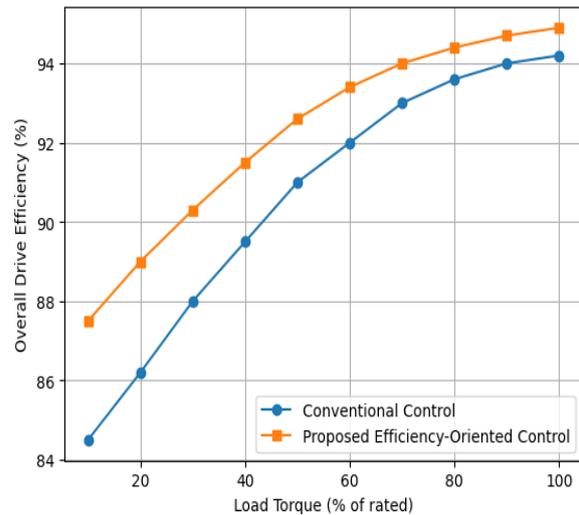

Fig. 3 Efficiency comparison under different load conditions

Fig. 3 shows performance of the efficiency of the drive when operated under different load conditions, the total drive efficiency performance of both control strategies is graphically illustrated in Fig. 3 in terms of load torque verses the overall drive efficiency. The performance is calculated by applying the unified model in (5) that includes converter and machine losses. As indicated in the figure, the proposed control is always more efficient over the whole operating range. This is mostly enhanced in light- and medium-load conditions, which are dominated by core losses, as well as switching losses. At low load levels (10–30% of rated torque), efficiency gains of approximately **2–3%** are observed due to adaptive i_d–i_q current selection and switching-frequency optimization. The efficiency improvement slowly decline but is not negative as the load nears the rated condition and this again proves that the proposed strategy does not affect the full-load performance.
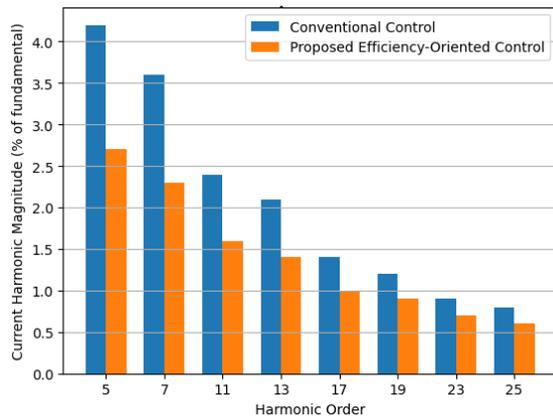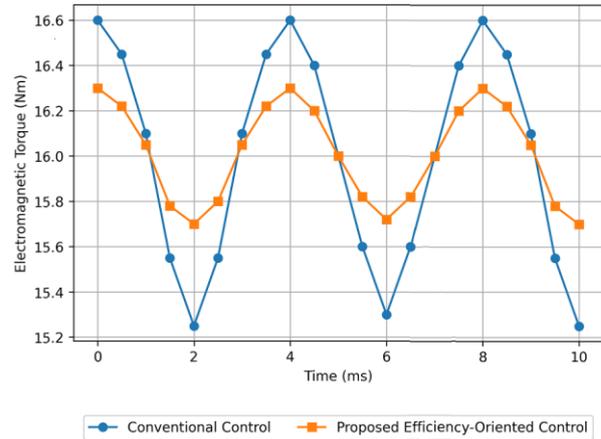
Fig. 4(a) Harmonic Spectrum

Fig. 4(b) . Torque Ripple

The effect of the suggested control on the power quality and mechanical performance are published in Fig. 4 that demonstrates the comparison between the harmonic spectrum of the stator current and the electromagnetic torque ripple. As can be seen in Fig. 4(a), with the proposed control, dominant low-order harmonics, especially the 5th and 7th components, are extremely suppressed, which are highly challenging to the grid-connected operation. Therefore the sum of the grid current total harmonic distortion (THD) decreases to around 4.3 percent as compared to the estimated 6.8 percent under the traditional controlling approach. This is by means of coordinated current regulation, multilevel modulation and optimum selection of switching-frequency.

A comparison of both control schemes in the electromagnetic torque beating at steady-state is provided in Figure 4(b). Although the average torque and level remain the same with both approaches, the suggested approach generates a much smoother torque signal with a smaller variation between peaks. Torque ripple is also decreased by almost 8.4 percent when using the traditional control, compared to 3.8 percent when using the proposed strategy, which can be linked with better mechanical smoothness and decreased stress of the drive components. In order to obtain a succinct quantitative comparison, the main performance indicators that were obtained based on Figs. 3 and 4 are summarised in Table 2.

Table 2 . Performance Comparison Between Conventional and Proposed Control

Metric	Conventional Control	Proposed Control
Peak efficiency (%)	94.2	94.9
Converter losses (W)	410	340
Torque ripple (%)	8.4	3.8
Grid current THD (%)	6.8	4.3

On the whole, the findings indicate that efficiency-oriented control strategy proposed can be used to simultaneously enhance the energy efficiency, power quality, and mechanical performance. The uniform efficiency of the operating range, along with minimised harmonic distortion and ripple of torque, affirm the success and effective viability of the proposed technique of grid-connected and industrial multilevel-converter fed electrical machine drive.

7. DISCUSSION

The findings given in the section above show that the addition of loss awareness to the control loop of multilevel converter-fed electrical machine drives brings about quantifiable and uniform performance recovery in terms of efficiency, power quality, and mechanical smoothness. This part explains the nature behind these improvement, the attendant trade-offs and the implications of these approaches to grid-connected and industrial applications. It can be explained by the adaptive selection $i_d - i_q$ of current components and switching-frequency optimization, and these results in improved efficiency as seen in Fig. 3, specifically in light- and medium-load conditions. With fixed current references and fixed switching frequency, conventional vector control reaches off-peak operating point at part load. Contrastingly, the suggested control dynamically modulates the flux-generating current and switching action and thus minimises core losses and converter switching losses. Copper losses predominate when the load enters rated operation conditions, thus capacity to optimise diminishes hence the less yet positive improvement in efficiency at high lead levels.

Fig. 4(a) shows the harmonic spectrum, which indicates a very significant side benefit of the given approach. Different high-level harmonics are greatly eliminated by the synchronisation between the existing regulation and multilevel modulation as well as switching-frequency selection. The direct result of this improvement is a lower grid current THD and improved compliance to standards of grid power quality. Notably, the gains are attained without any additions to the filtering hardware, or without any additions to the control complexities which makes the integrated control design particularly effective. As it can be seen in figure 4(b) the proposed control enhances mechanical performance too by minimising electromagnetic torque ripple. This is due to a smaller harmonic interaction between the inverter and the machine and smoother torque waveform is ensured by optimised current trajectories. Reduced torque ripple is especially useful in industrial drives, because it leads to less mechanical stress, less acoustical noise and wear over time of the drive train components.

In control perspective, one of the strengths of the proposed strategy will be its hierarchical and deterministic organisation. The loss-conscious optimization layer is a supervisory level, whereas the internal dq-axis current control loops are still of the classical PI based structure. This separation guarantees that there is a tradeoff between optimization of efficiency and system stability as well as transient response. Besides, the method is compatible with generic digital controllers, and is not based on data-driven or learning-based methods, which increases dependability and industrial adoption. The above benefits must not be neglected, and some trade-offs must be recognised. The success of the proposed strategy will be determined by the preciseness in converter and machine loss models. Change in parameters with change in temperature or ageing can be relevant to loss estimation and hence compromise optimality. Nonetheless, they can be reduced by the periodic updating of the parameter or the application of the simple online estimation method without changing the underlying control structure. On balance, the discussion proves that the efficiency-oriented approach to control is the optimal and realistic solution to the problem of coping with the enhancement of the functioning of multilevel converter-fed electrical machine drives. Given the simultaneous improvement of efficiency, power quality, and mechanical smoothness in a classical control system, the method holds great potential in implementation in the present grid-connected and industrial drive systems.

8. CONCLUSION

The current paper has set forth an efficiency related design and control model of multilevel converter-fed electric machine devices having application both in power systems connected with the grid and also in industrial motors. The proposed method improves the traditional dq-axis vector control by providing a hierarchical control structure by explicitly defining converter and machine loss modeling and dynamically identifying the optimal operating conditions without impacting dynamic performance or grid power quality. The results of the simulation showed that the proposed control strategy for the problem in question attains a steady increase in efficiency throughout the vast spectrum of load conditions, the greatest improvements being observed during the operation with light- and medium-load. The combination of adaptive $i_d - i_q$ current selection and a switching-frequency optimization method were effective to minimise converter switching loss and machine core loss, and direct to a larger overall drive efficiency. Moreover, the given solution enhanced power quality and reduced dominant low-order current harmonics, as well as the grid current total harmonic distortion. This was also improved by an increase in mechanical performance by decreasing by a large amount the electromagnetic torque ripple which produces a smoother operation and mechanical stress reduction. The suggested control solution has a deterministic and modular design, and this allows the solution to be compatible with the standard digital control platforms and make implementation possible in the existing industrial drive systems. Having no prerequisites to data-driven or learning-based methods, the scheme provides a stable and scalable way of enhancing efficiency, power quality, and operational resilience in contemporary multilevel converter based fed electrical machine operate drives. The experimental validation based on the real-time hardware platform and exploring parameter adaptation to the effects of temperature and ageing, as well as applying the proposed framework to more complex multilevel topologies and wide-bandgap semiconductor devices, will be the future work.

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