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Power-Quality Improvement Features In Grid Interconnection of Wind Energy Source at the Distribution Level

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Abstract— **The increased power demand, the depletion of the fossil fuel resources and the growth of the environmental pollution has led the world to think seriously of other alternative sources of energy. So renewable energy resources (RES) are being connected to the distribution systems, mostly done by using power electronic converters. A new control strategy for achieving maximum advantage from these grid-interfacing inverters which are when installed in 3-phase 4-wire distribution systems is given in this paper. With the inverter control, the inverter can be used as a multi-function device, which includes the function of: 1) power converter to inject power generated from RES to the grid, and 2) shunt APF to compensate current unbalance, load current harmonics, load reactive power demand and load neutral current. These functions of the inverter can be done either individually or simultaneously. The proposed inverter with the control when connected, helps the 3-phase 4-wire linear/non-linear unbalanced load at point of common coupling appear as balanced linear load to the grid. With MATLAB/Simulink simulation studies, the proposed control technique is demonstrated and evaluated here.**

Index Terms—Active power filter (APF), distributed generation (DG), distribution system, grid interconnection, power quality (PQ), renewable energy, Point of common coupling (PCC).

I. INTRODUCTION

Electrical power is the most widely used source of energy for our household's equipments, industries and work places. Population and industrial growth have led to significant increases in power consumption over the past decades. Natural resources like petroleum, coal and gas that have driven our industries, power plants and vehicles for many decades are becoming depleted at a very fast rate. This is an important issue, which has motivated nations across the world to think about alternative forms of energy which utilize inexhaustible natural resources. The combustion of conventional fossil fuel across the globe has caused increased level of environmental pollution .Several international conventions and forums have been set up to address and resolve the issue of climate change. These forums have motivated countries to form national energy policies dedicated to pollution control, energy conservation, energy efficiency, development of alternative and clean sources of energy. Renewable energy like solar, wind, and tidal currents of oceans is sustainable, inexhaustible and environmentally friendly clean energy. Due to all these factors, wind power generation has attracted great interest in recent years. Undoubtedly, wind power is today's most rapidly growing renewable energy source.

Distributed generation (DG) is termed as the integration of Renewable energy source (RES) at the distribution level. The number of distributed generation (DG) units, including both renewable and nonrenewable sources, for small rural communities not connected to the grid and for small power resources connected to the utility network has grown in the last years. The integration of renewable energy systems (RESs) in smart grids (SGs) is a challenging task, mainly due to the intermittent and unpredictable nature of the sources, typically wind or sun. So for the reliable operation of the system, continuous control is needed. This can be obtained by the help of digital control and power electronic devices which may improve the power quality of the system at the PCC. The quality of power in the system is mainly affected by the harmonic current produced by the non-linear loads and power electronic based instruments [1],[2].

In the distributed system, the intermittent RES is connected using current controlled voltage source inverters. New control strategies for grid connected inverters with PQ solution have been proposed. In [3] an inverter operates as active inductor at a certain frequency to absorb the harmonic current. The control performance may be decreased because of the complexity in exact calculation of network impedance in real time. In [4] a cooperative control of multiple active filters based on voltage detection for harmonic damping throughout a power distribution system is proposed. In [5], a control strategy for renewable interfacing inverter based on p-q theory is proposed. This strategy includes both load and inverter current sensing which is required to compensate the load current harmonics.

Voltage harmonics which is caused by non-linear load current harmonics can create serious PQ problem in the power system network. To compensate this, Active power filters (APF) are extensively which may result in additional hardware cost. This paper suggests how to include the APF in the conventional inverter interfacing renewable with the grid, without any additional hardware cost.

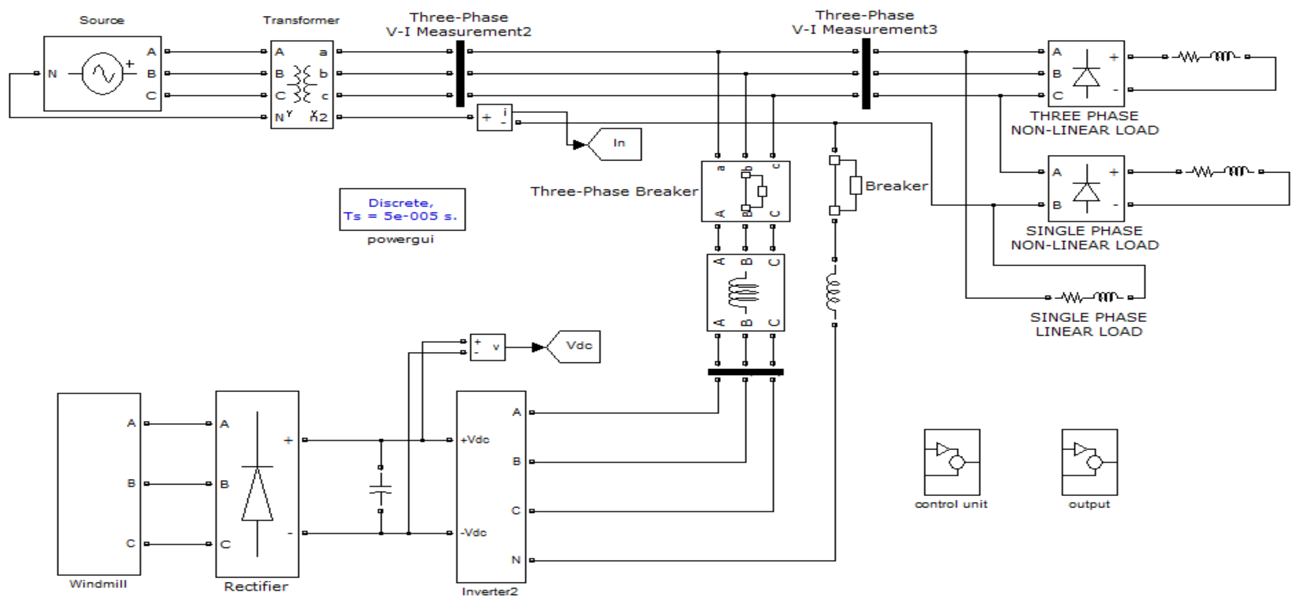

Fig. 1. Schematic of proposed renewable based distributed generation system.

In this paper that the grid-interfacing inverter can effectively be utilized to perform the following four important functions: 1) transfer of active power harvested from the renewable resource (wind); 2) load reactive power demand support; 3) current harmonics compensation at PCC; and 4) current unbalance and neutral current compensation in case of 3-phase 4-wire system. All the four objectives can be accomplished either individually or simultaneously with adequate control of grid-interfacing inverter. So without additional hardware cost the PQ constraints at the PCC can therefore be strictly maintained within the utility standards.

The paper is so arranged in the order that: Section II describes the system under consideration and the controller for grid-interfacing inverter. Section III includes a digital simulation study is presented. Section IV finally concludes the paper. The paper is so arranged in the order that: Section II describes the system under consideration and the controller for grid-interfacing inverter. Section III includes a digital simulation study is presented. Section IV finally concludes the paper.

II. SYSTEM DESCRIPTION

As in the Fig.1 the system consist of an RES connected to the dc-link of a grid-interfacing inverter. The voltage source inverter interfaces the renewable energy source to the grid. The RES may be a DC source or an AC source with rectifier coupled to dc- link. The fuel cell and photovoltaic energy sources generate power at variable low dc voltage, but the production of power in variable speed wind turbine is variable ac voltage. So before connecting on to a dc-link, the power generated from these renewable sources needs to be power conditioned (i.e., dc/dc or ac/dc). Usually the fuel cell integration is provided by using a unidirectional DC/DC converter (to obtain regulated high voltage DC), an inverter and a filter in order to accommodate the DC voltage to the required AC voltage (single phase or three phase).

A. DC-Link Voltage and Power Control Operation

Because of the intermittent nature of RES, the generated power is of variable nature. The dc-link connected aids in transferring this variable power from RES to the grid. RES are represented as current sources connected to the dc-link of a grid-interfacing inverter. The current injected by renewable into dc-link at voltage level V_{dc} can be given as

$$I_{dc1} = \frac{P_{RES}}{V_{dc}} \qquad (1)$$

Where P_{RES} is the power generated from RES.

The current flow on the other side of dc-link can be represented as,

$$I_{dc2} = \frac{P_{inv}}{V_{dc}} = \frac{P_G + P_{Loss}}{V_{dc}} \qquad (2)$$

Where, P_{INV} - total power available at grid-interfacing inverter side, P_G- active power supplied to the grid and inverter losses, and P_{LOSS} - inverter losses. If inverter losses are negligible then, $P_{RES} = P_G$.

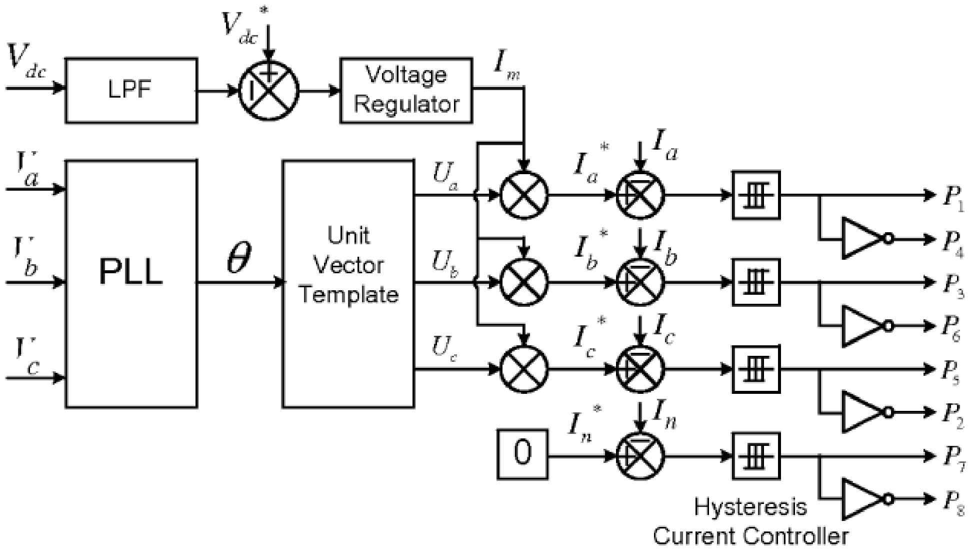

Fig. 2. Block diagram representation of grid-interfacing inverter control.

B. Control of Grid Interfacing Inverter

The control diagram of grid- interfacing inverter for a 3-phase 4-wire system is shown in Fig. 2. To compensate the neutral current of load, a fourth leg is provided to the inverter. The proposed approach is mainly concerned about the regulation of power at PCC during three conditions like, when 1) $P_{RES} = 0$; 2) P_{RES} < total power (P_L); and 3) $P_{RES} > P_L$. During the power management operation, the inverter is controlled in such a way that it always draws/ supplies fundamental active power from/ to the grid. If the load connected to the PCC is non-linear or unbalanced or the combination of both, the given control approach also compensates the harmonics, unbalance, and neutral current. By the control, duty ratio of inverter switches are varied in a power cycle in order to get the combination of load and inverter injected power to be appearing as balanced resistive load to the grid. The exchange of active power in between renewable source and grid can be obtained from the regulation of dc-link voltage.

Thus the output of dc-link voltage regulator results in an active current (I_m). The multiplication of this active current component (I_m) with unity grid voltage vector templates (U_a,U_b, and U_c) generates the reference grid currents (I^*_a,I^*_b , and I^*_c) for the control process. The reference grid neutral current (I^*_n) is set to zero, being the instantaneous sum of balanced grid currents. Phase locked loop (PLL) is used to generate unity vector template from which the grid synchronizing angle (θ) is obtained.

$$U_a = \mathrm{Sin}(\theta) \qquad (3)$$

$$U_b = \mathrm{Sin}(\theta - \frac{2\pi}{3}) \qquad (4)$$

$$U_c = \mathrm{Sin}(\theta + \frac{2\pi}{3}). \qquad (5)$$

To eliminate the presence of switching ripples on the dc-link voltage and in the generated reference current signals, the actual dc-link voltage (V_{dc}) is sensed and passed through a first-order low pass filter (LPF). The difference of this filtered dc-link voltage and reference dc-link voltage (V^*_{dc}) is given to a discrete- PI regulator to maintain a constant dc-link voltage under varying generation and load conditions. The error in the dc-link voltage $V_{dcerr(n)}$ at the sampling instant is given by:

$$V_{dcerr(n)} = V^*_{dc(n)} - V_{dc(n)} \qquad (6)$$

At the n^{th} sampling instant, output of discrete-PI regulator is expressed as,

$I_{m(n)} = I_{m(n-1)} + KP_{PVdc}\,(V_{dcerr(n)} - V_{dcerr(n-1)} + K_{IVdc}\,Vdcerr(n)$ (7)
Where $KP_{PVdc}=10$ and $K_{IVdc}=0.05$ are proportional and integral gains of dc-voltage regulator. The instantaneous values of reference three phase grid currents are computed as

$I^*_a = I_m . U_a$ (8)

$I^*_b = I_m . U_b$ (9)

$I^*_c = I_m . U_c$ (10)

If any neutral current is present, due to the loads connected to the neutral conductor, it is compensated by forth leg of grid-interfacing inverter and thus it will not disturb the grid by drawing it form the grid. ie, the reference current for the grid neutral current is considered as zero and can be expressed as

$I^*_n = 0$ (11)

The reference grid currents $(I^*_a, I^*_b, I^*_c \text{ and } I^*_n)$ are compared with actual grid currents (I_a, I_b, I_c and I_n) to compute the current errors as

$I_{aerr} = I^*_a - I_a$ (12)

$I_{berr} = I^*_b - I_b$ (13)

$I_{cerr} = I^*_c - I_c$ (14)

$I_{nerr} = I^*_n - I_n$ (15)

These current errors are then used to produce the switching pulses (P1 to P8) by giving them to hysteresis current controller. The hysteresis controller then generates the switching pulses for the gate drives of grid-interfacing inverter. By the following state space equations, the average model of 4-leg inverter can be obtained.

$$\frac{dI_{Inva}}{dt} = \frac{(V_{Inva} - V_a)}{L_{sh}} \quad (16)$$

$$\frac{dI_{Invb}}{dt} = \frac{(V_{Invb} - V_b)}{L_{sh}} \quad (17)$$

$$\frac{dI_{Invc}}{dt} = \frac{(V_{Invc} - V_c)}{L_{sh}} \quad (18)$$

$$\frac{dI_{Invn}}{dt} = \frac{(V_{Invn} - V_n)}{L_{sh}} \quad (19)$$

$$\frac{dV_{dc}}{dt} = \frac{(I_{Invad} + I_{Invbd} + V_{Invcd} + V_{Invnd})}{C_{dc}} \quad (20)$$

In this, V_{Inva}, V_{Invb}, V_{Invc} and are the three-phase ac switching voltages produced at the output terminal of inverter. These inverter output voltages can be modeled in terms of instantaneous dc bus voltage and switching pulses of the inverter as

$$V_{inva} = \frac{P_1 - P_4}{2} V_{dc} \quad (21)$$

$$V_{inva} = \frac{P_3 - P_6}{2} V_{dc} \quad (22)$$

$$V_{inva} = \frac{P_5 - P_2}{2} V_{dc} \quad (23)$$

$$V_{inva} = \frac{P_7 - P_8}{2} V_{dc} \quad (24)$$

The charging currents I_{Invad}, I_{Invbd}, I_{Invcd} and on dc bus due to the each leg of inverter can be expressed as

$I_{Invad} = I_{Inva}\,(P_1 - P_4)$ (25)

$I_{Inv\,bd} = I_{Invb}\,(P_3 - P_6)$ (26)

$I_{Invcd} = I_{Invc}\,(P_5 - P_2)$ (27)

$I_{Invad} = I_{Inva}\,(P_7 - P_8)$ (25)

The switching pattern of each IGBT inside inverter can be formulated on the basis of error between actual and reference current of inverter, which can be explained as:
If $I_{Inva} < (I^*_{Inva} - h_b)$, then upper switch S_1 will be OFF (P_1=0) and lower switch S_4 will be ON (P_4 =1) in the phase "a" leg of inverter.
If $I_{Inva} > (I^*_{Inva} - h_b)$, then upper switch S_1 will be ON(P_1=0) and lower switch S_4 will be OFF (P_4 =0) in the phase "a" leg of inverter.
Where h_b is the width of hysteresis band. On the same principle, the switching pulses for the other remaining three legs can be derived.

III. SIMULATION RESULTS

For the simulation studies to verify the proposed control approach to achieve multi-objectives for grid interfaced DG systems connected to a 3-phase 4-wire network is carried out using MATLAB/Simulink. To achieve balanced sinusoidal grid currents at unity power factor (UPF) despite of highly unbalanced nonlinear load at PCC under varying renewable generating conditions, a 4-leg current controlled voltage source inverter is actively controlled. A RES with variable output power is connected on the dc-link of grid-interfacing inverter. On the PCC, an unbalanced 3-phase 4-wire nonlinear load, whose unbalance, harmonics, and reactive power need to be compensated, is connected. The waveforms of grid voltage (V_a,V_b,V_c), grid currents (I_a,I_b,I_c,I_n), unbalanced load current (I_{la},I_{lb},I_{lc},I_{ln}) and inverter currents (I_{inva}, I_{invb},I_{invc},I_{invn}) are shown in Fig. 3. The corresponding active-reactive powers of grid (P_{grid},Q_{grid}) , load(P_{load}, Q_{load})and inverter are shown in Fig. 4. Positive values of grid active-reactive powers and inverter active-reactive powers, shows that these powers flow from grid side towards PCC and from inverter towards PCC, respectively. The positive signs indicates the active and reactive powers are absorbed by the load.

At t= 0s, the grid-interfacing inverter is not connected to the network (i.e., the load power demand is totally supplied by the grid alone). Therefore, before time t= 0.72s, the grid current profile in Fig. 3(b) is identical to the load current profile of Fig. 3(c). The grid-interfacing inverter is connected to the network at t= 0.72s. When the inverter is connected to the grid, the inverter starts injecting the current to the grid in such a way that the profile of grid current starts changing from unbalanced non linear to balanced sinusoidal current as shown in Fig. 3(b). As the inverter supplies the load neutral current demand, after t=0.72 s the grid neutral current becomes zero. The inverter starts injecting active power generated from RES ($P_{RES} \approx P_{inv}$), at t=0.72s. If the generated power is more than the load power demand, then the additional power is fed back to the grid. After time 0.72 s, the grid receive power from RES which is indicated by the negative sign (-P_{grid}). The grid-interfacing inverter also supplies the load reactive power demand locally. So

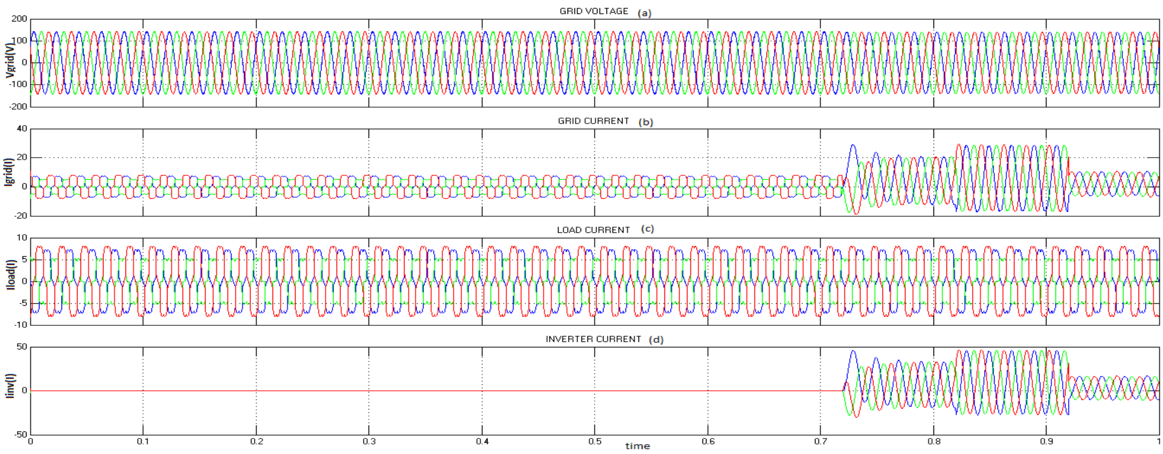

Fig. 3. Simulation results: (a) Grid voltages, (b) Grid Currents (c) Unbalanced load currents, (d) Inverter Currents.

when the inverter is connected to the grid, then the grid only supplies/receives fundamental active power.

To evaluate the performance of system under variable power generation from RES, at t=0.82 s, the active power from RES is increased. As a result, the magnitude of inverter current is also increased. As the load power demand is considered as constant, this additional power generated from RES flows towards grid, which can be noticed from the increased magnitude of grid current as indicated by its profile. Then the power available from RES is reduced at t=0.92s. From Fig. 3 the corresponding change in the inverter and grid currents can be observed. The active and reactive power flows between the inverter, load and grid during increase and decrease of energy generation from RES can be noticed from Fig. 4. In order to facilitate the active and reactive power flow the dc-link voltage across the grid- interfacing inverter during different operating condition is maintained at constant level

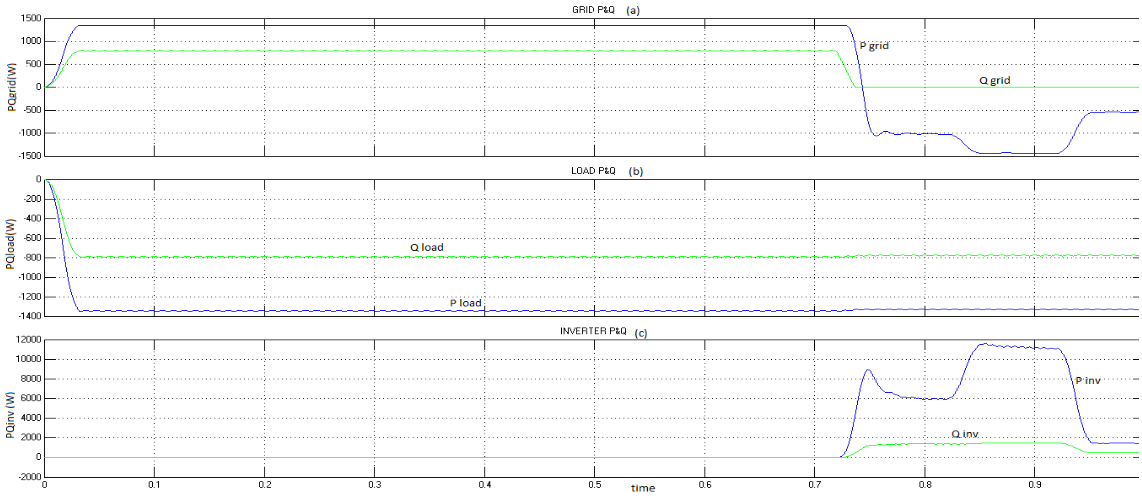

Fig. 4. Simulation results: (a) PQ-Grid, (b) PQ-Load, (c) PQ-Inverter.

. Thus from the simulation results, it is evident that the grid-interfacing inverter can be effectively used to compensate the load reactive power, current unbalance and current harmonics in addition to active power injection from RES. This enables the grid to supply/ receive sinusoidal and balanced power at UPF.

IV. CONCLUSION

This paper has introduced a new control of an existing grid interfacing inverter to improve the power quality at PCC for a 3-phase 4-wireDGsystem. The ability of the grid-interfacing inverter to be effectively used for the power conditioning without affecting its normal operation of real power transfer is also shown.

The grid-interfacing inverter with the proposed technique can be utilized to:

i) inject real power generated from RES to the grid, and/or,
ii) operate as a shunt Active Power Filter (APF).

This approach helps to improve the quality of power at PCC without the need of additional power conditioning equipment. Extensive MATLAB/Simulink results have validated the proposed approach and have shown that the grid-interfacing inverter can be utilized as a multi-function device. The simulation demonstrates that the PQ enhancement can be achieved under three different scenarios: 1) $P_{RES} = 0$; 2) $P_{RES} < P_{Load}$; and 3) $P_{RES} > P_{Load}$. The current unbalance, current harmonics and load reactive power, due to unbalanced and non-linear load connected to the PCC, are compensated effectively such that the grid side currents are always maintained as balanced and sinusoidal at unity power factor. The fourth leg of inverter prevents the load neutral current from flowing into the grid side by compensating it locally. When the power generated from RES is more than the total load power demand, the grid-interfacing inverter with the proposed control approach not only fulfills the total load active and reactive power demand (with harmonic compensation) but also delivers the excess generated sinusoidal active power to the grid at unity power factor.

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