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Investigation of low voltage DC microgrid using sliding mode control

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ABSTRACT

As the requirement of power increases, the use of renewable energy resources has become prominent. The power collected from these energy resources needs to be converted using AC-DC or DC-DC converters. The control of DC-DC converters is a complex task due to its non-linearity in the converter introduced by the external changes such as source voltage, cable resistance and load variations. Converters are to be designed to obtain a well stabilized output voltage and load current for variable source voltages and load changes. Droop control method is the most abundantly used technique in controlling the parallel converters. The major limitations of the conventional droop control technique are circulating current issues and improper load sharing. The proposed work is to resolve these issues by integrating Sliding Mode Controller (SMC) with the converter in order to enhance the performance of DC microgrid. The entire control system was designed by taking the output voltage error as the control variables. Similarly, droop control with PI and PID were also performed and all these techniques were simulated and compared using MATLAB/Simulink. The experimental results show that the proposed sliding mode controller technique provides good overall performance and is suitable against variable voltage and load changes.

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1. INTRODUCTION

In recent years, as the consumption of power increased it is essential to increase the generation on demand. Nowadays the use of renewable energy such as solar, wind and tidal are effectively used for power generation. These renewable sources need not be at same place, they can be at different places based on energy availability. So, even the role of microgrid has become prominent. A microgrid is a small-scale power supply network that can generate, distribute and control power in a small community. Microgrid comprises of renewable power generating sources and storage devices that make it profoundly reliable and proficient. Proper integration between distributed energy resources, battery storage system and different loads delivers good quality of power to the consumers. An interesting aspect of the microgrid is its capability to work in grid-connected mode and islanded mode [1-4].

Based on the nature of signals, Microgrids are classified into AC and DC microgrids. With the ongoing research, DC microgrid proves to be more significant than AC microgrid. The concern of AC microgrid involves reactive power issues, power factor correction, frequency control, poor voltage regulation and presence of skin effect. DC microgrids are potentially more efficient, economical, more reliable, easy to store and control than AC microgrid. Current research on DC microgrids deals with system design, control modeling and stability of various converters and integration of DERs with the microgrid [5]. The operation of LVDC microgrid relies on the converter selection and control system design. In DC microgrid, DERs are integrated with converters to a common LVDC bus. By connecting DC-DC converters in parallel, effective current at the load can be doubled and if one module fails the other module compensates the output load [6, 7]. Integration of DERs with DC-DC converters to a common bus involves a lot of limitations such as improper load sharing, circulating currents and poor voltage regulation due to varying sources voltages, cable resistances and load changes.

The droop control technique eliminates the circulating currents of the parallel converters and improves the voltage regulation. Many droop control techniques have evolved from recent years and the most familiar control strategies are centralized (Master-Slave) and decentralized (Voltage Droop). In Mater Slave current method, a common bus for sharing current is used among converters to produce proficient bus voltage. The main constraint is that the whole system will get affected if there is a failure in the signal of the current bus [8]. Droop control design involves two controller loops, the first one is a voltage control loop which improves the voltage regulation and the second one is a current control loop which reduces the circulating currents in between the parallel converters [9-12]. The control loops using PI, PID and SMC have been designed to stabilize the performance of load current and output voltage. The PI control loops have been discussed in [13]. The major limitations of the droop control method are poor regulation of voltage and current sharing in between parallel converters because of droop activity. The significance of cable resistance is discussed in [14]. An alternative droop control method using fixed droop resistance using lag compensator is discussed in [9]. Since fixed droop resistance is only permitted to fixed load, an adaptive droop control method is discussed in [15-21].

The objective of this project is to solve the existing stability issue in the DC microgrid occurred by the source voltage variations and load changes. The most common techniques in DC microgrid for controlling converters are PI and PID controllers. These are the two control techniques that reduce the error by comparing the voltage reference with the output of the converter. Since the converters are non-linear [22, 23]. A non-linear control technique has been implemented to solve the problem. Sliding mode controller is an effective tool used in designing robust controllers for non-linear dynamic systems operating under varying conditions. SMC has guaranteed linear stability and works for dynamic load and line uncertainties. [24-28], SM controller provides fast dynamic response, high robustness and good stability for large load variations [29-30]. Simulation results of performance characteristics of PI, PID and SMC are carried out to validate the research work.

2. SYSTEM CONFIGURATTION

This section deals with load sharing and current circulating issues of LVDC microgrid. A DC microgrid consisting of fixed input voltages V_{i1} and V_{i2} with dc-dc converters and common load is demonstrated in Figure 1. A DC-DC buck converter is taken as an interfacing converter between the source and the LVDC bus. The equivalent circuit of the parallel converters can be modeled as source voltage in series with the cable resistance connected to a common load as demonstrated in Figure 2. Voltage level plays a prominent role in deciding the system efficiency, cost and operation of DC microgrid. In this work, 48 V is taken as the LVDC bus voltage, Since the telecommunication industry, for the most part, utilizes 48 V and is the best choice for the LVDC transmission system. The case studies for parallel DC-DC converters are shown below in Table 1.

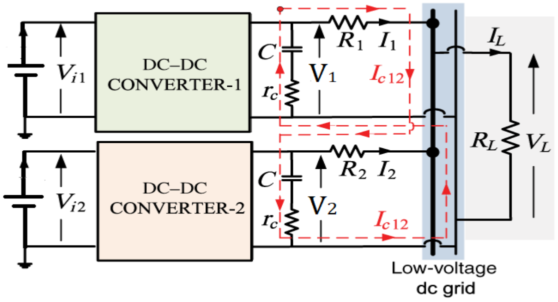


Figure 1. Parallel DC-DC converters

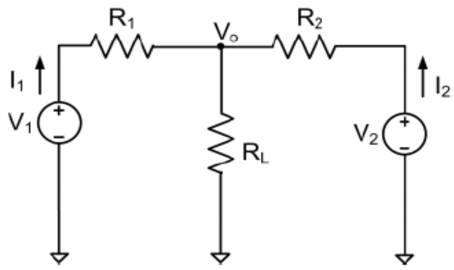


Figure 2. Equivalent Circuit

Table 1. Case study of parallel DC-DC converters

Case	Cable resistances R_1, R_2	Output voltages V_1, V_2	Output currents I_1, I_2	Output powers P_1, P_2	Circulating currents I_{C12} - I_{C21}
1	Equal	Equal	Equal	Equal	Zero
2	Unequal	Equal	Unequal	Unequal	Not zero
3	Equal	Unequal	Unequal	Unequal	Not zero
4	Unequal	Unequal	Unequal	Unequal	Not zero

Applying Kirchhoff's Voltage Law in Figure 2.

$$V_1 - I_1R_1 - (I_1 + I_2)\,R_L = 0 \qquad (1)$$

$$V_2 - I_2R_2 - (I_1 + I_2)\,R_L = 0 \qquad (2)$$

I_1 and I_2 can be obtained by solving the equations (1) and (2).

$$I_1 = \frac{(R_2+R_L)V_1 - R_LV_2}{R_1R_2+R_1R_L+R_2R_L} \qquad (3)$$

$$I_2 = \frac{(R_1+R_L)V_2 - R_LV_1}{R_1R_2+R_1R_L+R_2R_L} \qquad (4)$$

Circulating currents can be expressed as

$$I_{C12} = -I_{C21} = \frac{V_1 - V_2}{R_1+R_2} = \frac{I_1R_1 - I_2R_2}{R_1+R_2}\ (\text{if } R_1 \neq R_2) = \frac{I_1 - I_2}{2}\ (\text{if } R_1 = R_2) \qquad (5)$$

3. PROPOSED CONTROL METHOD

In this section, the detailed modeling and procedure for designing of sliding mode droop controller is being discussed. A droop resistance is incorporated within the controller to stabilize the system during variable source and load changes.

3.1. System modelling

The first step in designing SMC involves developing of desired control variables for the converter. The control signals given to the SMC are proportional to the control variables of the converter (i.e., voltage or current, etc.). Output voltage error is taken as the input control variable for the converter. Figure 3 demonstrates the general block diagram of SMC.

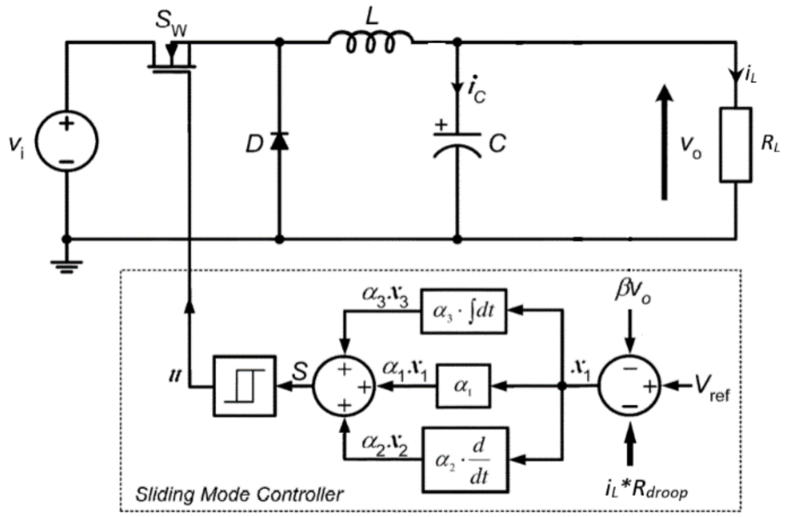


Figure 3. General block diagram of SMC buck converter

The control variable 'x' of the converter can be expressed as:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} V_{ref} - \beta V_o - I_l R_{droop} \\ \frac{d}{dt}(V_{ref} - \beta V_o - I_l R_{droop}) \\ \int (V_{ref} - \beta V_o - I_l R_{droop})\, dt \end{bmatrix} \tag{6}$$

Where, x_1 = Proportional voltage error
x_2 = Differential voltage error
x_3 = Integral voltage error

Where, β – Feedback factor
i_L, i_c – Load and Capacitive currents
R_{droop} – Droop Resistance
V_{ref}, V_i, V_o – Reference, Source and Output voltages

3.2. Controller design

Sliding mode controller design is derived from variable control matrix. The controller design calculations are given below.

$$\begin{aligned} S &= \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 \\ &= \alpha_1 x_1 + \alpha_2 \frac{dx_1}{dt} + \alpha_3 \int x_1\, dt \end{aligned} \tag{7}$$

solving the equations from (6) and (7) we get

$$V_{control} = -K_{p1} i_c + K_{p2} (V_{ref} - \beta V_o - I_l R_{droop}) + \beta V_o \tag{8}$$

$$V_{ramp} = \beta V_o \tag{9}$$

$$\text{Where, } K_{p1} = \beta L \left(\frac{\alpha_1}{\alpha_2} - \frac{1}{R_L C}\right) \tag{10}$$

$$K_{p2} = LC \frac{\alpha_3}{\alpha_2} \tag{11}$$

$$\frac{\alpha_1}{\alpha_2} = \frac{10}{T_S} \tag{12}$$

$$\frac{\alpha_3}{\alpha_2} = \frac{25}{\delta^2 T_s^2} \tag{13}$$

where $\alpha_1, \alpha_2, \alpha_3$ are sliding coefficients, δ is the damping constant, T_s is the desired settling time. The overall control structure of SMC is demonstrated in Figure 4. The controller design parameters for SMC are mentioned in Table 2.

Table 2. Parameters of SMC

Parameters	Values
Input Voltage V_{in}	100 V
Output Voltage V_o	48 V
Reference Voltage V_{ref}	48 V
Switching Frequency f_s	10 KHZ
Inductance L	0.479 mH
Capacitance C	271.25 µF
Inductor Resistance r_L	0.002 Ω
ESR of capacitor R_C	0.03 Ω
Peak to peak inductor current ripple percentage $2\Delta i_L$	10%
Ripple factor of peak output voltage ΔV_o	5%
Droop Resistance R_{droop}	0.6 Ω
Duty Cycle D	0.48
K_{P1}	1.6466
K_{P2}	2
β	0.95
Damping Constant δ	0.5
Settling Time T_s	2.546ms

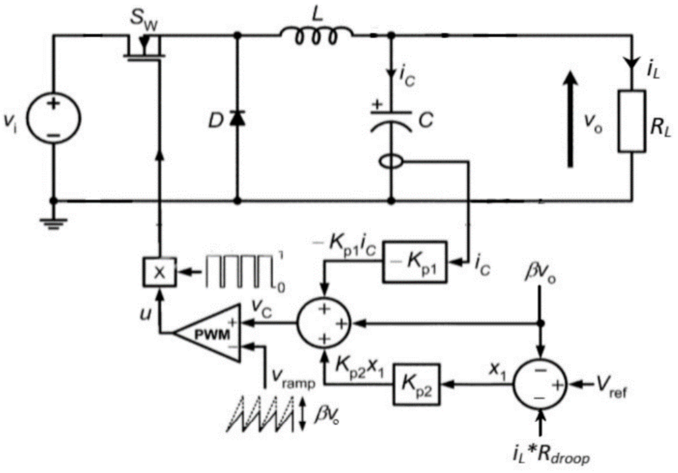


Figure 4. Control Structure of SMC buck converter

4. SIMULATION RESULTS

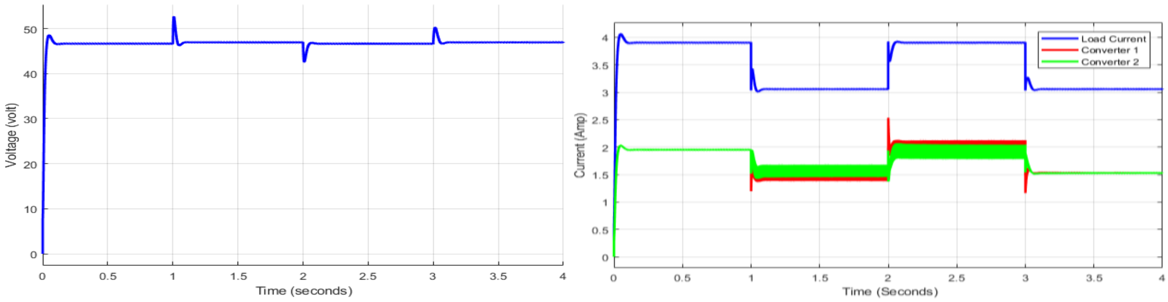
Different droop control techniques were performed on two parallel buck converters using MATLAB/Simulink and the output results were recorded. To compare the performance of SMC with PI and PID controller's different converter parameters such as varying cable resistance, varying source voltage and load changes are considered at different intervals as mentioned in Table 3.

Table 3. Input voltage and load variations at different intervals

Time(sec)→	0-1	1-2	2-3	3-4
Input Voltage of Converter-1	100V	100V	110V	100V
Input Voltage of Converter-2	100V	110V	100V	100V
Load Resistance (R_L)	11.95 Ω	15.36 Ω	11.95 Ω	15.36 Ω

4.1 PI controller with same cable resistance, different source voltage, and different load

Figure 5 displays the load voltage and output currents waveform of PI controller at different loads 11.95 Ω, 15.36Ω and varying source voltages 100 V and 110 V. It is observed that the load voltage is almost equal for different loads with peak overshoots during load variations and output current is 3.893 A for 11.95 Ω and 3.048 A for 15.36Ω. It is observed that the converters undergo large oscillations at varying conditions.

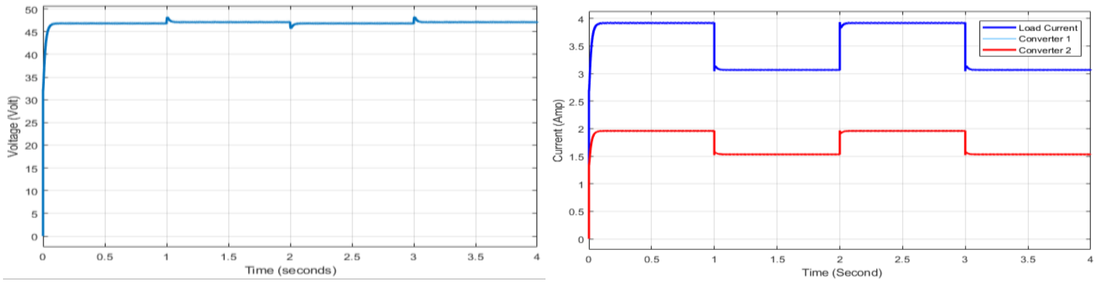


(a) (b)

Figure 5. Simulation results for PI controller with same cable resistance
(a) Load voltage (b) output currents and load current of converters

4.2 PID controller with same cable resistance, same source voltage and different load

Figure 6 displays the load voltage and output currents waveform of PID controller at different loads 11.95 Ω, 15.36 Ω and equal source voltages 100 V. It is observed that the load voltage is almost equal for different loads with little disturbances during load variations and output current is 3.909 A for 11.95 Ω and 3.14 A for 15.36 Ω. PID Controllers only work for same cable resistances, same source voltages because the controller gain values are tuned for prefixed values and the system doesn't work for variable voltages and varying cable resistances.

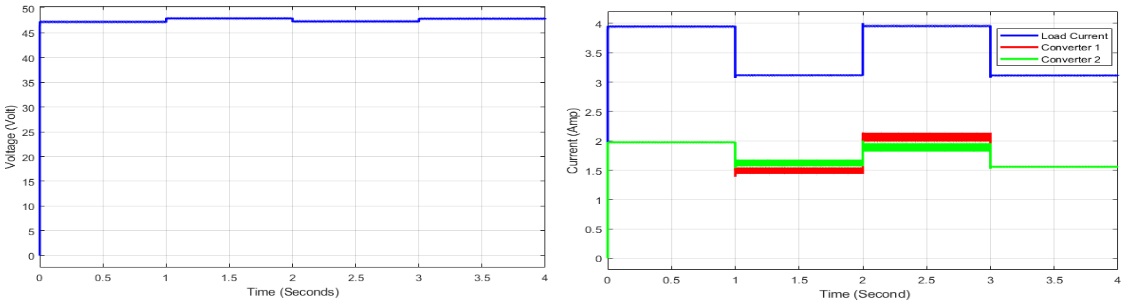


(a) (b)

Figure 6. Simulation results for PID controller with same cable resistance
(a) Load voltage (b) output currents and load current of converters

4.3 SMC with same cable resistance, different source voltage and different load

Figure 7 displays the load voltage and output currents waveform of SM controller at different loads 11.95 Ω, 15.36 Ω and varying source voltages 100 V and 110 V. It is observed that the load voltage is equal for different loads with no disturbances during load variations and output current is 3.954 A for 11.95 Ω and 3.118 A for 15.36 Ω.

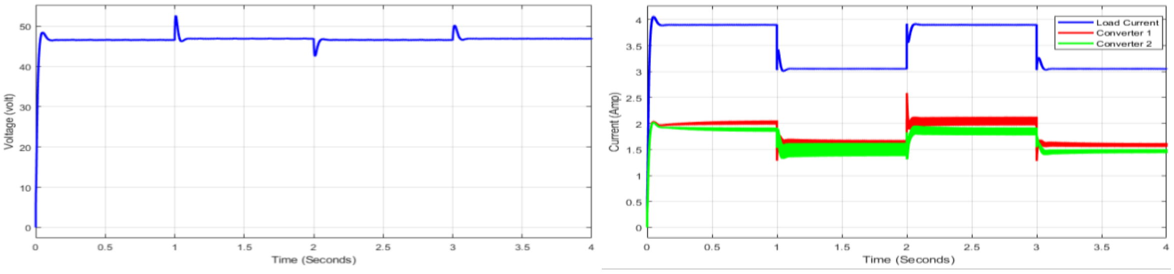


(a) (b)

Figure 7. Simulation results for SM controller with same cable resistance
(a) Load voltage (b) output currents and load current of converters

4.4 PI controller with different cable resistance, different source voltage and different load

Figure 8 displays the load voltage and output currents waveform of PI controller at different loads 11.95 Ω, 15.36Ω and varying source voltages 100 V and 110 V. It is observed that the load voltage is almost equal for different loads with peak overshoots during load variations and output current is 3.889 A for 11.95 Ω and 3.045 A for 15.36Ω. It is observed that the converters undergo large oscillations at varying conditions.



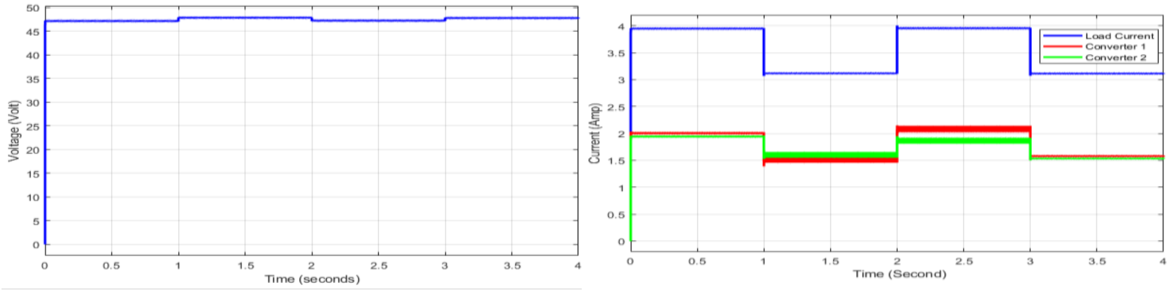
(a) (b)

Figure 8. Simulation results for PI controller with different cable resistance
(a) Load voltage (b) output currents and load current of converters

4.5 SMC with different cable resistance, different source voltage and different load

Figure 9 displays the load voltage and output currents waveform of SM controller at different loads 11.95 Ω, 15.36 Ω and varying source voltages 100 V and 110 V. It is observed that the load voltage is equal for different loads with no disturbances during load variations and output current is 3.952 A for 11.95 Ω and 3.103 A for 15.36 Ω.

The results shown in Table 4, 5, 6, 7 it can be justified that the SMC gives better results for varying conditions and is more stable than PI and PID controllers. Droop control using PI controller results in peak overshoots and disturbances during varying source voltage and load changes and PID controller resolves the issue by adding a derivative term but the main disadvantage of PID is that it works only for same voltage and same cable resistance because the system parameters are autotuned in such a way that the system works only for fixed values. These disturbances in PI and PID results in poor voltage regulation, improper load sharing and circulating current issues. SMC offers better voltage regulation and minimizes the circulating currents.



(a) (b)

Figure 9. Simulation results for SM controller with different cable resistance
(a) Load voltage (b) output currents and load current of converters

Table 4. R_1= 0.1 Ω, R_2= 0.1 Ω, R_L= 11.95 Ω, T= 0-1s and 2-3s, P=192W

	V_1	V_2	V_L	I_1	I_2	I_L
PI	46.72	46.72	46.52	1.947	1.947	3.893
PID	46.71	46.71	46.50	1.954	1.954	3.909
SMC	47.44	47.44	47.25	1.977	1.977	3.954

Table 5. R1= 0.1 Ω, R2= 0.1 Ω, RL= 15.36 Ω, T= 1-2s and 3-4s, P=150W

	V_1	V_2	V_L	I_1	I_2	I_L
PI	46.96	46.96	46.81	1.524	1.524	3.048
PID	46.94	46.94	46.78	1.57	1.57	3.14
SMC	48.05	48.05	47.9	1.559	1.559	3.118

Table 6. R1= 0.1 Ω, R2= 0.15 Ω, RL= 11.95 Ω, T= 0-1s and 2-3s, P=192W

	V_1	V_2	V_L	I_1	I_2	I_L
PI	46.68	46.76	46.48	2.004	1.885	3.889
SMC	47.43	47.52	47.23	2.012	1.94	3.952

Table 7. R_1= 0.1 Ω, R_2= 0.15 Ω, R_L= 15.36 Ω, T= 1-2s and 3-4s, P=150W

	V_1	V_2	V_L	I_1	I_2	I_L
PI	46.93	46.99	46.77	1.585	1.46	3.045
SMC	47.82	47.89	47.66	1.566	1.537	3.103

5. CONCLUSION

In this paper, different control techniques for controlling a low voltage microgrid were designed and simulated using MATLAB/Simulink. The test cases were recorded by varying different parameters and the output characteristics were compared. The PI and PID control methods offer a simpler control system than the SMC method and also offer faster operation but cause peak overshoots and increase in settling time during the start and cause slight disturbances in the output voltage and load current during variations in source voltage and load. The proposed SMC droop control method offers a better stable response by eliminating the peak overshoots and oscillations without affecting the system.

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