Coupling Low-Voltage Microgrids into Mid-Voltage Distribution Systems

University of Notre Dame – General Electric
Project Statement of Work (SOW)
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Project Motivation

Bundling of distributed energy resources (DER) and loads in a microgrid provides a convenient way of increasing the amount of distributed generation in the main grid [Lasseter11]. This is accomplished by connecting multiple low voltage (LV) microgrids to the mid voltage (MV) feeder line as shown in Figure 1. Autonomous control of these microgrids can be used to control how power is exported back to the main grid.

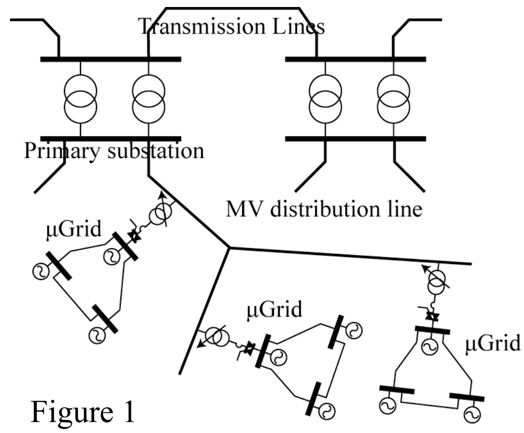


Figure 1

Prior work [Lasseter02, Piagi06] has demonstrated that microgrid power quality can be preserved under islanding and reconnection. Such reconnections, however, may have an adverse impact on the operation of the MV distribution network. Exporting power from coupled microgrids to the MV distribution line is complicated by the voltage rise problem [Master02]. Voltage rise occurs in long MV distribution lines when a DER downstream from the primary substation begins exporting power to the grid [Repo03, Ueda08]. In general, the voltage at the DER connection point will have to increase to enable power export back to the primary substation (unless certain compensating policies are used). This increase in voltage at the DER will impact voltages throughout the distribution network in a way that may cause overvoltage limits to be tripped back at the primary substation. Furthermore, connecting additional DER on the distribution line may interfere with automated line drop compensation (LDC) schemes [Viawan07].

The objective of this project is to develop a distributed approach for managing the coupling of LV microgrids to a MV distribution feeder in a way that addresses the voltage rise problem. The project will treat the problem as an optimization problem that controls reactive power flows and adjusts tap-changing transformers in a manner that avoids the voltage rise problem while staying within power flow constraints of the system. We propose solving the problem in a distributed manner, building on event-triggered distributed algorithms that were developed for distributed power dispatch within microgrids [Wan10]. The main deliverables for this project will be 1) a distributed management scheme for coupled microgrids, 2) simulated verification of the proposed scheme, 3) a recommendation regarding the most appropriate communication technologies for implementing the scheme, and 4) a recommendation regarding the role of distributed estimation in monitoring MV network power quality.

Voltage Rise Problem

To better understand what must be controlled in this problem, let's first review the basics of the voltage rise problem. Voltage rise refers to the increase in voltage that occurs when one connects a device exporting power to the distribution network. The rise in voltage between the primary substation and the microgrid is $\Delta V = \frac{RP + XQ}{V_{\mu G}}$ where *R* is the line resistance, X is the line reactance, P and Q are the real and reactive power delivered by the microgrid, and $V_{\mu G}$ is the voltage at the microgrid's connection point to the distribution line. To combat voltage rise, one needs to reduce the numerator in the ΔV equation by either reducing the microgrid power P or importing reactive power Q to the microgrid. Either of these methods have problems associated with them.

Decreasing the exported power, P, reduces the DER capacity in the system and increasing reactive power absorbed by the microgrid may result in large currents that exceed the capacity of the generators and loads in the microgrid. *On-line tap changing transformers (OLTCT) may also be used to adjust voltage levels at the microgrid connection point [Hird04, Kulamala07, Nagata08].* This is one of the standard methods that utilities use to manage the voltages in the MV distribution line. Allowing direct control of the tap-changing transformer by the microgrid, however, may interfere with existing utility load management practices [Viawan07]. *One may also adjust the line voltage and reactive power through the coordinated use of switched capacitor banks and multi-step voltage regulators [Grainger85, Dugan03]. Capacitor banks are used to inject reactive power into the distribution line and when their use is coordinated [Roytelman95, Baran99] with voltage regulators or OLTCT's, they can be effective in maintaining distribution line voltage profiles.*

Instead of relying solely on tap-changing transformers with volt/var control through capacitor banks, one can also adjust the active and reactive power delivered or absorbed by the microgrid. The reactive power Q of a single DER can be selected in a way that minimizes its impact on line voltage (thereby avoiding interference with LDC policies) [Carvalho08]. When multiple DER's (or microgrids) are connected to the distribution line, however, these ideal reactive power setting must be coordinated so they don't exceed the maximum limits of what can be safely handled within the microgrid. What this suggests, of course, is that managing the active and reactive power of multiple microgrids should be posed as an optimization problem in which the constraints are the power limits within the microgrid and the cost function is related to minimizing the voltage rise effect.

Prior work has already proposed such optimization problems for reactive control of voltage rise. Formulations of this problem will be found in [Baran07, Madureira07, 08, Nguyen08, Zhou07]. Note that this earlier work has only proposed these problems in the context of adding DER's to the distribution line, not microgrids. But regardless of this, one finds the underlying problem formulation to be the same. This problem can be stated as follows [Madureira08]

$$\begin{array}{ll} \text{minimize:} & \sum_{i=1}^{N} (P_{\text{loss}} + \mu G_{\text{shed}}) \\ \text{subject to:} & \underline{V} \leq V \leq \overline{V} \\ & \underline{Q} \leq Q \leq \overline{Q} \\ & \underline{P}_{\text{Ln}} \leq P_{\text{Ln}} \leq \overline{P}_{\text{Ln}} \end{array}$$

where P_{loss} are the MV real power loses and μG_{shed} is the amount of generation that is shed in each LV microgrid. The decision variables in this optimization problem are the reactive power and active power set points for each microgrid. One may also control the taps on load transformers. The inequality constraints in this problem consist of constraints on the MV bus voltages, V, and reactive powers, Q. The last constraint limits the real power, P_{Ln}, flowing through the distribution lines. This optimization problem, therefore seeks to minimize the change in voltage over the distributed line, P_{loss}, without unduly reducing the microgrid power imported into the main grid. The primary constraints of concern involve the voltages within the MV distribution satisfying the power quality constraints and capacity constraints of the system.

Proposed Approach

The above optimization problem is very similar to *network utility maximization* (NUM) problems [Kelly98] that have been used in computer network flow control. This suggests we can use distributed algorithms [Low99, Palomar07, Johansson07] to solve the problem. In this case, "distributed" means that the computational agent managing the microgrid's point of common coupling (POCC) will determine how much real and reactive power should be dispatched within the microgrid. This decision is only based on the POCC terminal voltages and currents as well as the voltages and currents of its *immediate neighbors*. Under this approach to dispatch, the configuration of the coupled microgrids is not stored in a centralized manner. Each POCC is responsible for maintaining its own configuration data. The advantage of this distribution is that it makes it easier to update and reconfigure the network in the event that a microgrid is added or removed from the MV distribution line. The system, therefore, becomes easier to maintain because it is self-configuring. This so-called *plug-and-play* functionality is desirable for it makes it easier for end-users to maintain and upgrade coupled microgrids without having to worry about reconfiguring the entire MV line.

Figure 2 (next page) illustrates how the dispatch algorithm would interact with General Electric's (GE) microgrid energy management (MEM) controllers. The left hand side of the figure is a MV line similar to that shown in figure 1. *In this figure, we've added OLTCT's, capacitor banks and a step voltage regulator to represent an existing legacy method for volt/var control.* A computational *agent* (i.e. computer) is attached to each microgrid's POCC. These agents measure the voltages and currents at the POCC and control the dispatch of power within the microgrid. Each agent is also equipped with a *communication module*. These modules can, for instance, be transceivers in a mesh Wi-Fi network or a power line communication (PLC) subsystem. Over the communication network, microgrids that are physically adjacent with each other exchange their voltage/current measurements. The agents use this data to recompute new power set points through a gradient descent type computation. These set points are then used directly by the GE MEM controllers. The computation updates the set point power by following the gradient of a cost function that is augmented with a quadratic cost associated with the line power constraints. The computation is inherently distributed since it only needs to use measured voltages/currents from neighboring microgrids and it assures that the chosen power set points remain feasible with respect to the generator and line power constraints.

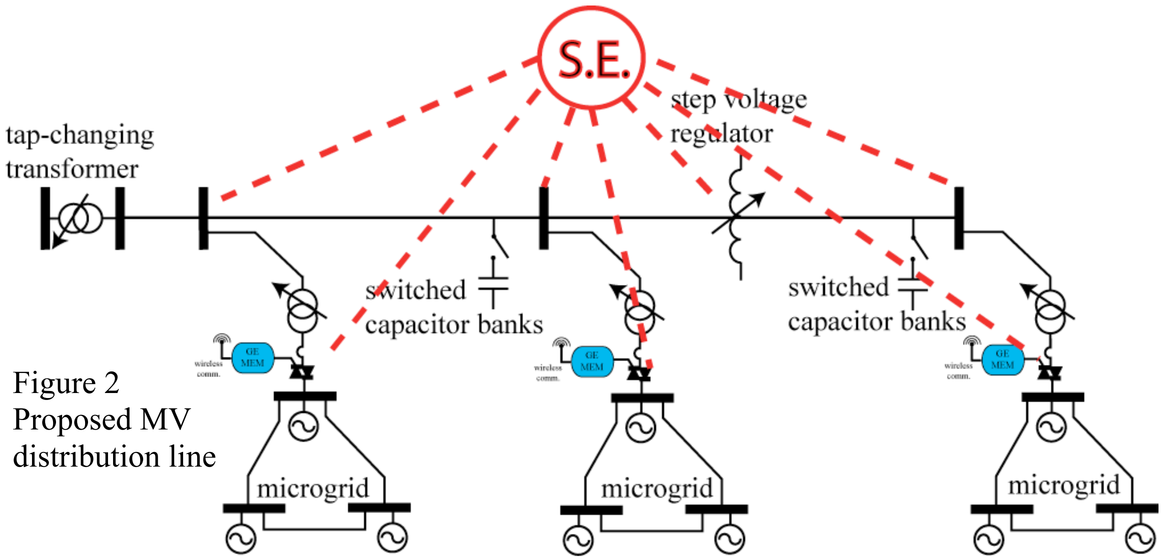


Figure 2
Proposed MV
distribution line

One potential problem with such distributed algorithms is that they *pull* information from their neighbors. What this means is that each time the algorithm updates its set point, it must obtain the latest voltage/current measurements for its neighbors. As a result, there is a great deal of message passing between agents within the system. This level of message passing has the undesirable effect of 1) increasing the cost of the communication infrastructure (it must be robust enough to handle the large traffic volume) and 2) increasing its susceptibility to outside interference through jamming. This project will study the use of *event-triggered* approaches to message passing. Under event-triggered message passing, one *pushes* rather than pulls information across the network. What this means is that an agent broadcasts (i.e. pushes) its voltage/current data to all of its neighbors whenever it sees a large enough deviation from its last transmitted measurements. One advantage of these event-triggered methodologies is that *fewer messages need to be passed between agents*. From prior experimental results [Wan09, Wan09a], we've shown that event-triggered message passing can reduce a distributed optimization algorithm's message passing complexity by *two orders of magnitude* relative to conventional dual-decomposition algorithms [Low99]. This reduction in message passing complexity therefore allows us to use less expensive wireless networking systems.

To the best of our knowledge there are relatively few distributed approaches for power dispatch control. One related work, however, will be found in [DeBrabandere07] in which a *gossip* mechanism for communication is introduced to manage voltage and frequency. Gossip based communication, however, still tightly couples network communication with the computation cycle. The *event-triggered* mechanisms for network communication being proposed in this project have been empirically demonstrated [Lemmon10] to greatly reduce overall message passing complexity.

While event-triggered message passing can greatly reduce communication bandwidth, it adds a degree of non-determinism to network traffic that alarms many real-time engineers [Albert04] concerned with safety-critical applications. This issue would certainly apply if we used event-triggered message passing to augment the low level decentralized controllers. Our proposal, however, uses event-triggered message passing at the higher supervisory level of the system. In this case, non-determinism and latency will not adversely affect the system's performance because these supervisory commands are not critical to the safe and stable operation of the system.

Communication Issues

GE-MEM controllers share information over a wide area communication network. To ensure the convergence of the proposed distributed algorithm, this shared information must be delivered with certain real-time guarantees. A key issue concerns the selection of the most appropriate networking technology at this scale. In many cases, wireless networking (WN) technologies such as mesh Wi-Fi (Troppos) have been suggested. Potential benefits of WNs include high data rates and ease of integration, monitoring, maintenance and upgrade. Some serious disadvantages of WNs, however, are vulnerabilities to security and operational failures such as susceptibility to malicious attacks through compromised communications nodes and denial of communications due to external radio frequency (RF) interference in the environment, including jamming. WN networks are also prone to reliability failures and service latencies, which would be particularly troublesome in safety-critical control systems. It is unclear whether or not these networks can be designed to provide the real-time guarantees required by the distributed optimization algorithm, and if security risk issues can easily be overcome.

One significant feature of the power grid is that the medium used for power distribution can be simultaneously used for power line communications (PLC). A second is that the power grid inherently provides an extensive communications infrastructure that would not be easily matched by alternative wired or wireless technologies. Because the infrastructure already exists, PLCs are the only communications technology with a comparable deployment cost to wireless technologies [Galli10]. To date, three primary bands have been used in PLC communications. Low data-rate PLCs (UNB-PLC) in the audio/low frequency (LF) bands have been used by utility companies for remote metering and load control. More recently, multicarrier techniques with higher data rate capacities have been deployed using narrowband PLCs (NB-PLC) in the CENELEC and FCC/ARIB frequency bands [Galli10], while broadband PCLs at high frequencies have primarily been used for home/building broadband applications (BB-PLC).

The PLC technology best-suited for MV smart grid power distribution management will depend on technical aspects as well as regulatory and business case considerations. Several considerations place NB_PLC techniques as a compelling candidate for MV smart grid applications [Galli10] including small frequency-dependent propagation losses (which limits the number of couplers and repeaters that need to be installed), availability of common spectrum world-wide, the potential for software-modems that are easily upgradable, and an inherent ability to coexist with popular PLC broadband standards since they employ difference frequency bands.

From a technical perspective, issues such as data rate, latency, and transmission power will be important considerations, but the primary technical challenges to MV smart grid operation involves the impact of channel impairments and mutual interference between the communications nodes. Assuming adequate repeater deployment, the PLCs are anticipated to be interference limited (rather than receiver noise-limited) through shared used of the medium and through channel impairments and channel disturbances inherent in the grid, for example, abrupt switching due to tap-changes may act as unwanted interference in the communication network. We anticipate that multicarrier techniques enabled in the NB-PLC frequency bands may help to limit the mutual interference between communications nodes in the MV distribution management network. Additionally, new modulation approaches, coding and interference suppression processing may be able to contribute to the overall networked communications solution. Finally, the potential to deploy communications aggregation points at repeater sites is anticipated to provide some flexibility in controlling mutual interference on the MV grid.

This project will investigate PLC communication technologies with particular emphasis on NB-PLCs, as well as feasibility studies on wireless solutions. We shall offer recommendations regarding physical layer and cross-layer solutions that may be applicable to smart grid communications for MV distribution management.

State Estimation Issues

The system being proposed in this project is an automated control system for managing reactive power in MV distribution lines. In any real-life implementation, however, the distribution network operators (DNO) need to monitor the system's performance in real-time. It would also be useful if these monitoring functions had some forecasting capabilities which require all information in the network to be transmitted to the DNO in a timely manner. *Problems occur if only some of the distribution connection points are instrumented.* In fact, at the MV distribution line level, there are usually only a limited number of measurements. It is therefore necessary to employ state estimators in the entire distribution network based on measurements available from a limited set of coupling points. This project will investigate the use of distributed state estimation (SE) as well as the feasibility of forecast-aided SE (FASE) methods for constructing and forecasting the overall distribution network's state from a limited set of real-time measurements. We shall provide technology surveys and feasibility studies.

Microgrid SE and FASE will play a critical role in the development of smart microgrids and there have been intensive investigations on those topics, see, e.g., [Korres2010], [Filho2009]. The outcomes of state estimation will expand the microgrids' visibility to the DNO on the distribution line. Since the integration of coupled microgrids into the MV distribution line can be very costly, *SE will help reduce the needs of protection schema and defer utility companies' capital investment in distribution and protection*. They will help ensure stability and reliability on the distribution line in the presence of voltage rises. In addition, SE and/or FASE can serve as arbitrator for the microgrid's individual optimization objectives, providing critical timely information for DNO to achieve global multi-attribute optimal solution for the entire distribution line. In essence, SE can serve as a mitigator of transient instability, an economic monitor, and an arbitrator to achieve globally optimum solution with respect to both reliability and economics. Forecast-aided estimation can help *reduce DNO's response time* to any disruptions, component failures or abrupt topological changes.

This project will begin by surveying estimation methods needed and appropriate models for SE and FASE at the MV distribution line level. For SE, we shall begin with traditional weighted least-squares (WLS) method and investigate the extent of complexity. We shall also study the feasibility of FASE for MV distribution line level as well as within the microgrid. We shall start with a Kalman state-space model and employ Kalman filter approach to obtain estimates of the states. The Kalman state-space model enables incorporation of dynamics of the states of the grid. It offers a more reliable and more accurate visualization of the interconnected systems. Critical issues of concerns will include model complexity, numerical stability and computational complexity in the implementation of the estimation algorithms. Some preliminary results have been obtained for reduced-order Kalman filter for FASE at the transmission level [Huang2011].

Statement of Work

This project proposes three specific tasks. These tasks will be conducted over a single year (start date 1/1/11). These tasks will 1) develop and simulate a distributed reactive control scheme for combating voltage rise in MV distribution networks, 2) make recommendations regarding the most appropriate communication technology required in implementing the proposed control scheme, and 3) study distributed estimation schemes used in estimating and forecasting the distribution network's state. Each of these tasks is discussed in more detail below.

TASK 1: Distributed Reactive Control in Coupled Microgrids

(M.D. Lemmon) – 1 month summer support – 1 graduate student

This task will develop a distributed algorithm for controlling reactive power delivered to LV microgrids coupled to a MV distribution network. The algorithm will adjust reactive power to counteract the voltage rise problem subject to power flow constraints within the microgrid. Simulation verification of the algorithm will be done on a MV distribution network similar to that in figure 2 *in which both on-line tap-changing transformers, capacitor banks, and voltage regulators are used to provide traditional volt/var control of the distribution line. One objective of this task will be to evaluate the impact that the proposed coupled microgrid algorithms will have on existing volt/var control mechanisms in the distribution line*. General Electric Energy will supply more concrete requirements on the distribution network to be simulated. Dr. M.D. Lemmon (University of Notre Dame) will direct this task with assistance from an introductory level Ph.D. student in the department of electrical engineering. Duration of the project will be for one year assuming a start date of 1/1/2011.

Milestones:

1) Algorithm Development – start 1/1/2011 – end 4/1/2011.
2) Simulation Model Development – start 1/1/2011 – end 6/1/201
3) Evaluation – start 6/1/2011 – end 11/1/2011
4) Final Report – start 11/1/2011 – end 11/30/2011.

Deliverables:

1) Interim Report (6/1/2011)

1) 2) Final Report (12/31/2011)
2) simPower simulation Files (12/312011).

TASK 2: Communication Network Technologies for MV Distribution Networks
(T. Pratt and J.N. Laneman) – 1 month academic year support – 1 graduate student
This task will survey PLC-based communications alternatives that potentially would enable the control of reactive power delivered to LV microgrids. The research will concentrate on PLC technologies and standards, including TWACS and the CENELEC EN 50065, IEEE 1901.2, and ITU-T G.hnem standards. The survey will help to identify PLC options and their suitability in terms of reliability, data rates, connectivity, latencies, coexistence, and other factors. Dr. T. G. Pratt will direct this task with assistance from an introductory level Ph.D. student in the department of electrical engineering. Dr. Laneman will provide support as needed in the area of networking technologies. The duration of the project will be for one year, assuming a start date of 1/1/2011

Milestones:
1) 1Q: Review of UNB-PLC and NB-PLC technologies and standards
2) 2Q: Characterization of interference, including NB-PLC channel impairments and interference from shared use
3) 3/4Q: Development and consideration of approaches for interference mitigation/control and tolerance to impairments
4) 4Q: Development of recommendations on the communications technologies to implement the control schemes

Deliverables
1) Interim Report (6/1/2011)
2) Final Report (12/31/2011)

TASK 3: Distributed Estimation and Forecasting in MV Distribution Networks
(Y-F Huang and V.J Gupta) – a fraction of 1 month summer support, 1 graduate student

This task will survey existing forecast-aided state estimation (FASE) algorithms suitable for MV distribution line in the presence of coupled microgrids and develop algorithms where possible. We shall examine the impact of FASE relevant to reliability and stability of coupled microgrids and investigate globally optimum solutions relevant to minimizing voltage rise and cost-effectiveness. Dr. Yih-Fang Huang will direct this task with assistance from an advanced level Ph.D. student and support from Dr. Vijay Gupta.

Milestones:
1) Survey technical requirements for state estimation at MV distribution line and microgrids (start 1/1/2011, end 4/1/2011).
2) Survey relevant SE and FASE algorithms and feasibility studies (start 1/1/2011, end 6/1/2011).
3) Develop estimation algorithms suitable for MV distribution line with coupled microgrids studied in this project (start 6/1/2011, end 11/1/2011).
4) Evaluation through simulation (start 10/1/2011, end 11/30/2011).

Deliverables:

1) Interim Report (6/1/2011)

2) Final Report (11/30/2011)

3) SimPower simulation files (11/30/2011).

TASK 4: Systems Integration

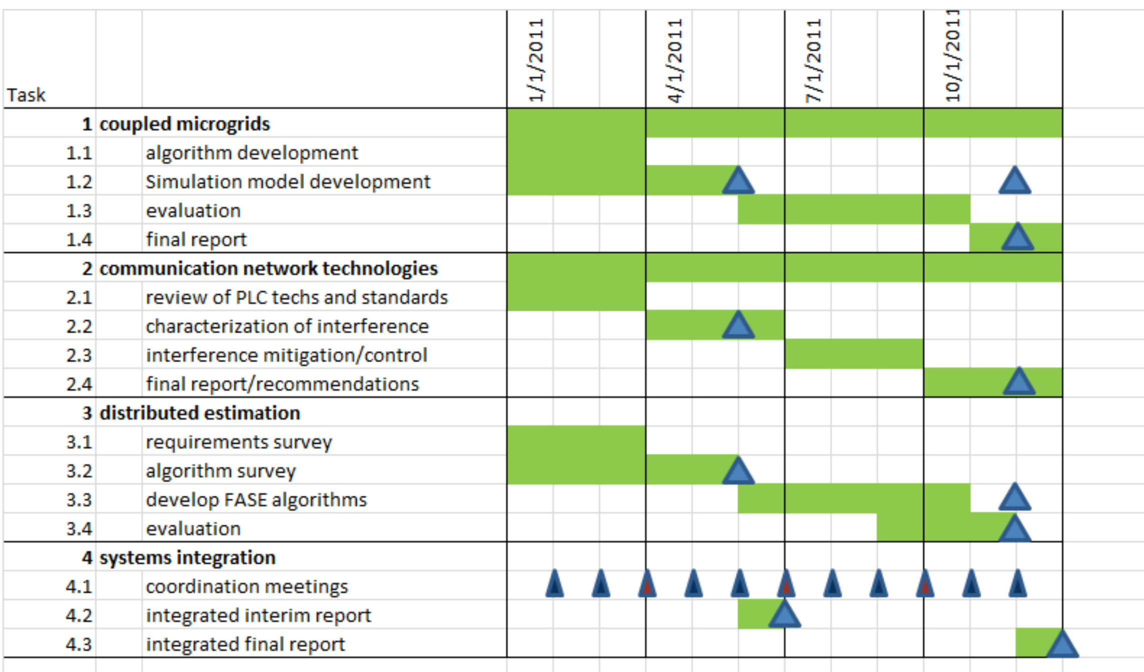
(Patrick Murphy – 0.5 month academic year support)

To ensure integration between microgrid controls, communications and estimation tasks, we will hold monthly coordination meetings between the principals and researchers. At the end of each quarter, this meeting will be expanded to include participation from GE subject matter experts, either in person or via webex. An integrated interim report (6/1/11) and final report (12/31/11) will be produced.

Deliverables:

1) Interim Report (6/1/2011)

2) Final Report (12/31/2011)



Proposed Budget and Justification

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