Circuit-Aware Distributed Optimal Voltage Control for Distribution Grids

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ABSTRACT

As pressures to decarbonize the electricity grid increase, traditionally used thermal power plants will increasingly be substituted by renewable energy sources (RES). RES differ from thermal power plants as they are smaller, distributed, much larger in number, and often located close to the consumer. Most RES such as photovoltaic (PV), batteries, and wind turbines require voltage inverters to connect them to the grid. Thus, we also refer to them as inverter-based resources (IBRs). Inverters are built of power electronics, making their dynamic response faster and more programmable than thermal generators that are commonly equipped with synchronous generators (SGs).

RES are more susceptible to fluctuations in the power they provide. Future power grids will frequently face a shortage of power supply by the transmission grid and therefore, must operate more independently by using local generation. Consequently, previous works have introduced islanded microgrid (MG) operation. In islanded mode, a MG is disconnected from the transmission grid and operates independently. When a MG operates in islanded mode, it must maintain its own voltage and frequency at certain reference values and dispatch the real and reactive power among the distributed generators (DGs), here modeled as IBRs.

In order to standardize its operation and functionality, hierarchical control methods for islanded MGs have been proposed. It divides the control structure into three layers, namely, primary, secondary, and tertiary control. A systematic representation of this structure is depicted in Figure 1. Economic dispatch and power flow optimization issues are usually considered in tertiary control. Solving the underlying optimal power flow (OPF) problems has proven to be challenging due to its large size and non-convexity. For the sake of simplicity, this work assumes that a tertiary controller is solved at the start of each simulation providing us with setpoints for the lower control levels. A novel current injection-based power flow model based on McCormick envelope convex relaxations is used to solve the tertiary control optimization problem [1]. Secondary control operates faster than tertiary control and slower than primary control. Voltage and frequency deviations are natural in many primary controllers, making secondary control indispensable to restore the frequency and voltage to their reference values before the OPF is solved. Primary control is deployed to maintain a generator's power balance. It takes local measurements of the provided reactive power and adapts the voltage magnitude in a proportional negative feedback loop. This setup is commonly referred to as droop control and has been traditionally deployed on large thermal power plants.

The transition from thermal power plants to smaller IBRs comes at the expense of the natural delay and inertia provided by the large rotating, mechanical masses of SGs. Some prior works have proposed modifying primary controllers as virtual SGs (VSGs) [2] or low-pass filtered droop-based controllers [3] to achieve sufficient delay with the objective of operating the MG in its old fashion and sustaining power grid dynamics. However, such implementations require large and expensive local energy storage units [4]. Alternatively, our work does not assume any artificial delay by the generators. This gives rise to new prominent circuit dynamics in the MG. This poses a challenge to secondary control, which must maintain grid stability under a new dynamic MG behavior [5].

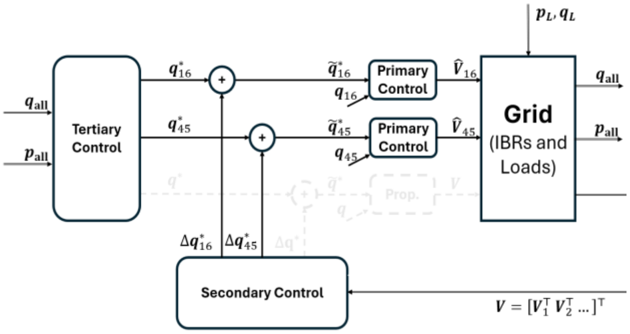

Figure 1: Microgrid control hierarchy.

In this work, we propose model predictive control (MPC) to address frequency and voltage restoration in islanded MGs under fast circuit dynamics in grids. MPC has several advantages over averaging proportional-integral (PI) control which is traditionally deployed for secondary voltage control. Firstly, it allows for an intuitive choice of a cost function. We can explicitly penalize voltage deviations from the set point provided by the tertiary controller. Additionally, penalizing the reactive power allows us to obtain sparse solutions that minimize line losses. MPC also has more flexibility in handling local deviations. We take the IEEE 123-node test feeder as depicted in Figure 2 as an example and assume a power (load) step at node 17c (where c denotes phase C of the three-phase network). In response, all generators (yellow nodes) will respond by providing the necessary reactive and active power injections. Ideally, all reactive power is provided by nodes in close proximity, i.e., node 16c and node 2c. Simulation results show how an averaging PI controller changes the reactive power set points of all generators on phase C equally. Thus, the voltages of node 16c, node 2c, and node 79c all change, despite the higher losses of reactive power traveling from node 79c to node 17c. In contradiction, MPC only changes the set points of nodes 2c and 16c, actively reducing power line losses. The simulated voltage of both, averaging PI and MPC are depicted in Figure 3. The last advantage of MPC is that bounds on reactive power inputs or voltages can easily be implemented in the formulation. For instance, if a cloud emerges to cover a solar PV unit, MPC can utilize weather predictions to pre-emptively reduce the power drawn from the PV beforehand.

Conventionally, MPC for secondary control is implemented in a centralized control scheme. Centralized control often suffers from susceptibility to single-point-of-failure, a lack of privacy, and little plug-in capabilities. Alternatively, a multi-agent system (MAS)-based distributed cooperative technique allows for more autonomy and flexibility. Such distributed approaches also reduce the computational burden and improve tractability, especially for larger networks with many nodes. The literature of distributed optimal control has so far mostly considered simple 3- to 4-node networks where all nodes are generators [6]. These algorithms are based on treating each generator unit as an agent. However, this comes at the expense of less flexibility in (i) integrating load nodes and (ii) creating clusters of computational units, along with no proof of functionality for distribution grids, which are generally larger. Other works have proposed clustered approaches [7], but these generally still require a central computational unit and often use lumped models of neighboring clusters. In this work, we propose a more general distributed optimization algorithm to solve the MPC problem for larger networks that represents clusters of nodes as agents and separates the global optimization into smaller problems for each cluster. These agents only need to iteratively communicate with their neighbors in order to solve the overall MPC problem. Further, we consider the short time constants of the generators by simulating the system with circuit dynamics [8], which will also be integrated into the MPC formulation.

This work is structured as follows. Section 2 discusses prior work on circuit models and the control hierarchy of power grids. Section 3 then presents the Circuit-Aware MPC and the distributed version will be discussed in Section 4. Section 5 simulates the new hierarchical controller on the IEEE 123-node test feeder and validates it against an averaging PI controller. Finally, Section 6 concludes this work and discusses possible future research directions.

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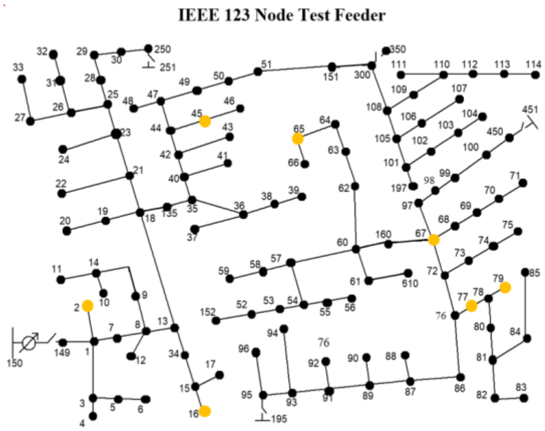

Figure 2: IEEE 123-node test feeder in islanded operation with multiple IBRs for power generation.

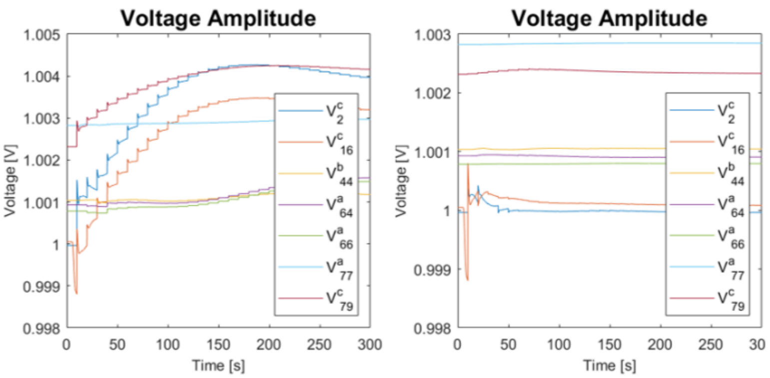

Figure 3: Simulation results comparing an averaging PI controller and circuit-aware MPC for secondary voltage control.

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