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Active power reference tracking in electricity distribution grids over non-ideal communication networks

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ABSTRACT

Distribution system operators may in the future control active power of selected consumers and generators in order to achieve a desired grid behavior. For cost efficient deployment, this control application may use existing communication infrastructure with non-ideal properties, i.e. imposing delays and losses. This paper considers a control strategy for this use-case, called Active Power Reference Tracking, and investigates its performance for a realistic grid scenario with non-ideal communication using a Real-Time Co-domain Testbed and extensive simulation experiments. Results from the distributed implementation in the testbed show the effectiveness of the controller and that the considered scenario of the reference tracking application is not significantly affected by delays and losses as originating from PLC communication in good conditions. The subsequent simulation experiments show the resilience of the reference tracking control application to end-to-end message delays up to the order of 3 control periods and to message loss up to approximately 70%.

1. Introduction

With the expected increase in decentralized energy resources, primarily from wind and photovoltaics (PV), electrical grids are exposed to new load and production scenarios that they were not originally designed for. Furthermore, new high consumer demands from Electrical Vehicle (EV) charging and heat pumps challenge existing distribution grid infrastructures [1,2]. This leads to several new challenges for the power grid. The most abundant renewable energy sources have fluctuating power generation which is independent of the power demand [3]. In a grid where such energy sources constitute a significant part of the total system capacity, the consumption must be balanced with the production and not the other way round as it is the case in the classical power grid. As a result, there is an increased interest in technologies to improve the operation of the distribution grids [4,5]. These mainly entail local energy storages, active control of energy injected into the electrical grid, flexible demand control (entailing both end-user managed demand response and autonomic demand control) for house-holds and EVs [6] as well as flexible power production and consumption in Medium Voltage (MV) grids.

Distribution System Operators (DSOs) may utilize the flexibility of the aforementioned grid assets in order to make the distribution grid follow a desired total power reference [7]. We call this use-case Active Power Reference Tracking, or just Reference Tracking, throughout the remainder of this paper. The control operations are relying on the ability to communicate measurements and set-points between the controllers and the assets [8]. Due to the heavy investments otherwise required by the DSO in deploying a dedicated communication network, it is attractive for the DSO to reuse existing general purpose communication networks, which may show variable communication delays and non-negligible message loss probabilities [9]. In many such cases, the distribution grid communication will share communication resources with other data traffic types, which will further contribute to variable communication network performance. It is therefore important to investigate the impact of non-ideal communication networks on the deployed Reference Tracking controller.

The goal of Reference Tracking is that LV and MV grids follow a power reference via the control of a subset of distribution system assets. Such control can reduce grid overload situations and can also reduce energy losses [10]. Further it is an enabler of future services such as partially autonomous micro-grid operation [11]. The performance of the Reference Tracking solution however needs to be evaluated as a

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distributed realization in the context of realistic grid scenarios. This paper therefore describes the implementation of an existing Reference Tracking controller [12] in a Real-Time Co-domain Testbed, and subsequently investigates the performance of this Reference Tracking controller for a realistic grid scenario. The testbed allows to analyze scenarios of ideal communication (with negligible delay and no loss) and subsequently compare to non-ideal communication scenarios at a very high technological readiness level due to its model accuracy and resolution. The Real-Time Co-domain Testbed [13] provides accurate emulation of the communication domain, control domain, and power domain in real-time, enabling studies of how these different domains interact during power grid operation. Furthermore, the paper assesses the performance bounds at which non-ideal communication network behavior significantly affects the Reference Tracking performance. The paper therefore contributes to an understanding of the requirements on the communication networks in order to support Reference Tracking in smart distribution grids.

Reference Tracking has been investigated in simulation models in [12,14]. This paper uses the same control architecture and the same controllers, however the Real-Time Co-Domain Testbed provides a much more detailed and fine-granular grid model and includes the actual communication protocol realizations in distributed physical entities. Reference [14] focused on communication network performance measurements in a lab setup for the communication links and only considered simplified LV grid scenarios. This paper uses some of the measured communication network delay traces from that reference in the testbed assessment of this paper by controlled injection of communication network delay traces. Simulations were so far the main instrument to analyze the impact of imperfect communication on other control use-cases: [15] considers the scenario of a wind-farm controller, [16] simulates the usage of electric vehicles in a vehicle-to-grid scenario, and [17] investigates the impact of communication outages on demand management schemes; the latter work also uses a combination of a distributed implementation in a similar real-time testbed together with simulations, while investigating a different use-case and control architecture. Several different controller designs have been studied, e.g. in [18,19], however with the focus on controller design and therefore often assuming ideal communication network conditions. Finally, different smart grid evaluation tools exist [20]. Ref. [21] provides an overview and also details the accuracy advantages of testbed approaches as opposed to pure simulation tools. The challenges of dealing with different domains are also addressed by various other approaches, see e.g. [22]. This paper uses the Real-Time Co-Domain Testbed from [13,23] in order to benefit from the following advantages: Applying model-based design for power system applications including smart grid; considering impact of communication technologies and their traffic on system control. Testing and validating control algorithms in a realistic environment and thus achieving Technology Readiness Level up to TRL 6. The paper combines this approach with simulation models using the framework from [24].

The remainder of the paper is structured as follows: Section 2 introduces the Reference Tracking use-case and the rationale for its performance metrics. Section 3 introduces the control architecture and describes the used controller from [12]. Section 4 describes the Real-Time Co-Domain Testbed realization, the emulation tools used within the testbed and the supporting simulation setup. Section 5 presents the results from the testbed analysis on the effectiveness of Reference Tracking both in an MV and LV grid and subsequently presents a detailed analysis using the combination of the testbed and simulation tools of the impact of the communication network performance for communication to LV assets.

2. Reference tracking in medium and low voltage grids

Fig. 1 illustrates the smart grid architecture used in this paper, and how the studied use-case (in the box on the right) connects to the rest of the smart grid. The two boxes on the left show the links to commercial and technical actors, out of which the communication network providers and the Distribution Management System (DMS) are directly involved in the considered use case. The links to the TSO, Aggregators, and commercial actors are also shown, but are considered out of scope of this paper as the investigated approach here uses direct asset control by the DSO. The right box in the figure shows in the center several secondary substations, which connect to the LV grids in the bottom that contain a variety of consumers of different types and also smaller electricity generators. The secondary substations connect these LV grids to a MV grid, which in turn is connected by a primary substation to the HV grid on top. The MV grid contains larger DERs and larger consumers. The primary substation can interact via a communication network, here called Wide Area Network (WAN), with assets in the Medium Voltage Grid and with other stakeholders and external systems, shown in the upper left part of the figure. The secondary substations are themselves assets in the MV grid and therefore are also reachable by the WAN. Furthermore, the secondary substations will interact with some of the LV grid assets via another communication network, here called Access Network (AN). The latter may be of heterogeneous type and the potential non-ideal properties of this network will shape a large part of the analysis later in this paper.

Considering that renewable energy resources are introduced in the LV and MV grid, new problems arise and are challenging the grid operation. The new types of energy resources challenge grid stability across the low voltage grid, due to production of power that is not coordinated to the local demand. Operating a grid without any control also implies possible high loss of energy due to non-optimal or un-coordinated operations of the renewable energy resources. Further, the existence of certain load characteristics as well as the option of not producing maximum power at the renewable energy resources offers some flexibility which may be helpful to support grids at higher levels.

Therefore the DSOs are obliged to

1. keep infrastructure and operation costs of the energy distribution grid low,
2. keep grid losses at a minimum,
3. stay in operation conditions inline with the deployed distribution grid infrastructure
4. follow requirements by the higher-layer grid operator.

In order to achieve these targets, we investigate the introduction of a networked control system that is able to control a subset of assets in the electrical grid. The focus in this paper is on the third target which is realized via a Reference Tracking capability, i.e. the ability of the MV or LV grid to follow a set-point.

We thereby assume that there are several flexible assets in the distribution grid, which shall be able to receive and follow an admissible set-point for active power from upper hierarchical controller(s). Note that in contrast to Demand Management and Demand Response schemes [17], there is no energy price and market involved in the control loop in this paper; the scenario of this paper for instance results, if the DSO directly interacts with some of the flexible assets itself, e.g. via specific contracts with the asset owners in order to support the reliable and efficient operation of the distribution grid. All flexible assets in the MV/LV grids must be able to send information about current active power production to upper hierarchical controller(s).

As the focus of this paper is the Reference Tracking functionality and its sensitivity to non-ideal communication network behavior, we here introduce the rationale for three performance metrics, which later drive the evaluation:

1. Reference Tracking error: Quantitative indicator of the grid's ability to follow the given reference.
2. Access network packet loss limit: An application layer packet loss probability below this boundary shall not lead to a significant